FIRE REGIMES AND SUCCESSIONAL DYNAMICS OF PINE AND OAK FORESTS IN THE CENTRAL APPALACHIAN MOUNTAINS

A Dissertation

by

SERENA ROSE ALDRICH

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2011

Major Subject: Geography

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ABSTRACT

Fire Regimes and Successional Dynamics of Pine and Oak Forests in the Central Appalachian Mountains. (May 2011)

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Chair of Advisory Committee: Dr. Charles W. Lafon

The role of fire in determining the structure and composition of many forested ecosystems is well documented (e.g. North American boreal forests; piñon-juniper woodlands of the western US). Fire is also believed to be important in temperate forests of eastern North America, but the processes acting here are less clear, particularly in xerophytic forests dominated by yellow pine (*Pinus*, subgenus *Diploxylon* Koehne) and oak (*Quercus* L.). In this study, I use dendroecological techniques to investigate fire history and vegetation dynamics of mixed pine-oak forests in the central Appalachian Mountains of Virginia. The study addresses three objectives: (1) develop a lengthy fire chronology to document fire history beginning in the late presettlement era and extending throughout the period of European settlement, industrialization and modern fire exclusion; (2) explore fire-climate relationships; and (3) investigate vegetation dynamics in relation to fire occurrence.

The study was conducted on three study sites within the George Washington National Forest. I used fire-scarred cross-sections from yellow pine trees to document fire history. Fire-climate relationships were investigated for each study site individually and all sites combined using superposed epoch analysis (SEA). Fire-history information was coupled with dendroecological data on age structure to explore stand development in relation to fire occurrence. Results of fire history analysis reveal a long history of frequent fire with little temporal variation despite changes in land use history. Mean fire intervals (MFI) ranged from 3.7–17.4 years. The most important change in the fire regime was the initiation of fire suppression in the early twentieth century. Results of SEA show that periodic droughts may be important drivers of fire activity. Drought the year of fire was important at two of the three study sites and when all sites were combined. Results of age structure indicate that vegetation development was clearly influenced by fire. Frequent burning maintained populations of yellow pine throughout the period of study until fire suppression allowed fire-sensitive hardwood trees and shrubs to establish. It is clear from this study that continued fire suppression will likely result in fire-tolerant pines and oaks being replaced by more mesophytic trees and shrubs.

ACKNOWLEDGEMENTS

Many people have contributed greatly to the completion of this project. First, I want to thank my committee chair, Dr. Charles Lafon, for his guidance, encouragement and mentorship; and to my committee members for their support and patience throughout the course of this research. I would like to thank Dr. Steven Quiring for sitting in on my dissertation defense in place of Dr. Tjoelker, and for providing valuable feedback for the climate portion of my dissertation. To Dr. Clarissa Kimber and Dr. Sarah Bednarz, thank you for being my mentor and friend; you will never know how much you have meant to me.

The completion of a project this size could not have been possible without the assistance of many people who helped with field work, data preparation/analysis, professional collaboration and funding. From Texas A&M: Jennifer Hoss, Adam Krustchinsky, Paul Rindfleisch, Alexis Green, John Aldrich, Gabe Burns, Kirk Stueve, Lauren Spencer, Jeremiah Wagstaff, and James Dalton. From The University of Tennessee: Dr. Henri Grissino-Mayer, Dr. Georgina DeWeese, Michelle Pfeffer, Lisa LaForest, Stockton Maxwell, Chris Underwood, Evan Larson, David Mann, Alison Miller, Daniel Lewis, Saskia van de Gevel and Jessica Brogden. From The Nature Conservancy: Judy Dunscomb. From the U.S. Forest Service: Steve Croy, Steve Smestad, Beth Buchanan, Jesse Overcash, Carol Hardy Croy, George Annis, Danny Wright, Butch Shaw, Herbie Huffman, Kenneth Hickman, Jason Hattersley, Zach Pennington, Mitch Kerr and Beth Atchley. Special thanks to Nelson Lafon for help in the field and providing our research team with a warm, dry, place to stay when we were working in the Blue Ridge. Funding for this project and my tenure at Texas A&M was generously provided by The Joint Fire Science Program, National Science Foundation (NSF) Doctoral Dissertation Research Improvement Grant; NSF Advancing Geospatial Skills in Science and Social Science (AGSSS) Fellowship and The Department of Geography at Texas A&M University.

Special thanks to Dr. Brian Williams and some of my best friends/fellow procrastinators of the Texas A&M SCS Thesis and Dissertation Writing Support Group. We have been through a lot of dissertating together and you've made the struggle much easier to endure! Finally, I would like to thank my family (and friends that I have adopted as family) for providing me with love, support, and infinite patience as I worked my way through three degrees! Thank you so much, I love you all!

NOMENCLATURE

AF	All Fire Events
AS	Any Season Fire Events
AW	Area-Wide Fire Events
DBH	Diameter at Breast Height
DS	Dormant Season Fire Events
GS	Growing Season Fire Events
GWNF	George Washington National Forest
LEI	Lower Exceedance Level
MF	Major Fire Events
MFI	Mean Fire Interval
NCDC	National Climatic Data Center
PDSI	Palmer Drought Severity Index
SD	Standard Deviation
SEA	Superposed Epoch Analysis
UEI	Upper Exceedance Level
USFS	United States Forest Service
WMI	Weibull Median Interval

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CHAPTER I

INTRODUCTION*

Fire is an important ecological process controlling vegetation development in many ecosystems (Bond & Keeley, 2005). The role of fire in determining the structure and composition of many forested ecosystems is well documented, e.g. North American boreal forests (Johnson, 1992); piñon (*Pinus edulis*)-juniper (*Juniperus* spp.) woodlands of the western United States (Romme *et al.*, 2009). Fire is believed to be important in the development of temperate forests of eastern North America as well (van Lear & Waldrop, 1989; Delcourt & Delcourt, 1997; Williams, 1998; Harrod *et al.*, 2000; van Lear & Brose, 2002), but the processes acting here are less clear, particularly in forests dominated by pine and oak (Abrams, 1992; Williams 1998; Parker *et al.*, 2001; Lafon, 2010). Xerophytic forests dominated by yellow pine (*Pinus*, subgenus *Diploxylon* Koehne) and oak (*Quercus* L.) in particular, rely on fire for regeneration and maintenance. However, fire exclusion during the twentieth century led to declines in the abundance of fire-tolerant pines and oaks and subsequent increases in hardwood trees and shrubs that are more sensitive to fire (Harmon 1982; van Lear & Waldrop 1989; Sutherland *et al.*, 1995; Harrod *et al.*, 1998, 2000; Williams, 1998; Elliott *et al.*, 1999; Nowacki & Abrams, 2008). Additionally, increased stand densities resulting from

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*Part of this chapter is reprinted with permission from "Three centuries of fire in montane pine–oak stands on a temperate forest landscape", by Aldrich, S.R., Lafon, C.W., Grissino-Mayer, H.D., DeWeese, G.G., and Hoss, J.A. 2010. *Applied Vegetation Science*, 13, 36–46.

decades of fire exclusion have made the stands more vulnerable to attack by native and exotic insects and pathogens (Lafon & Kutac, 2003; Waldron *et al.*, 2007).

The widespread lack of oak regeneration and the decline of endemic, fire-dependent species such as Table Mountain pine (*Pinus pungens* Lamb.) in the central Appalachian Mountains are of concern to resource managers because of the importance of these species for wildlife habitat and biodiversity. Federal, state and private land managers increasingly use prescribed fire to attempt to restore fire-dependent ecosystems. However, such burning programs are limited by a lack of information about the fire regimes that maintained the communities historically, or about vegetation responses to changing fire regimes (Williams, 1998; Elliott *et al*., 1999; van Lear, 2000; Welch *et al.,* 2000). Dendroecological techniques based on tree-ring analysis can be used to characterize historic fire regimes of forested ecosystems (Baisan & Swetnam, 1990; Abrams *et al.*, 1995; Grissino-Mayer & Swetnam, 1997; van Lear, 2000; Shumway *et al.*, 2001; Schuler & McClain, 2003) and to provide quantitative information necessary for the reintroduction of fire.

Fire is increasingly recognized as one of the most important processes missing from forests of the eastern US (Abrams, 1992; Waldrop *et al.*, 2003; Spetich, 2004). However, the frequency and severity of prescribed fire necessary for restoring xerophytic pine and oak ecosystems remains unclear (Welch *et al.*, 2000; van Lear & Brose, 2002; Waldrop *et al.*, 2002; Schuler & McClain, 2003). The dominant trees have adaptations to stand-replacing fires (e.g., serotinous cones) as well as mild surface burns (e.g., thick bark; prolific sprouting) (Sutherland *et al.*, 1995; Williams, 1998; Lafon &

Kutac, 2003; Waldrop *et al.*, 2003). Early research suggested that periodic stand-replacing fires were necessary for maintaining Table Mountain pine-pitch pine (*Pinus rigida*) stands (Zobel, 1969; Groeschl *et al.*, 1992; Turrill, 1998; Elliot *et al.*, 1999). More recent research suggests that frequent low-severity fires are sufficient to maintain the overstory, maintain the seed source and reduce the litter layer allowing successful Table Mountain pine regeneration (Waldrop *et al.*, 2003). However, the contrasting studies coupled with physiological adaptations to various fire-intensities suggest that mixed pine–oak stands were possibly maintained by a mixed-severity regime of frequent surface fires and occasional crown fires (Randles *et al.*, 2002).

Several paleoecological studies used sediment pollen and charcoal to reveal that fire was prevalent in eastern forests (Clark & Royall, 1996; Delcourt *et al.*, 1998; Welch, 1999; Lynch & Clark, 2002; Fesenmyer & Christensen, 2010), but the dendroecological dating of fire scars on trees offers the best direct evidence for the regular occurrence of fire (Shumway *et al.*, 2001; Dey, 2002). Until recently, few fire history studies using fire-scarred trees have been published for the Appalachian region (Fig. 1.1). Most of these studies were small; consisting of single sites with < 50 fire-scarred trees (see Table 1.1). Mann *et al.*, (1994) reconstructed a lengthy fire history of a rare, unlogged, hemlock-pine forest in Vermont (Fig. 1.1). Interpretations of fire-scar and tree germination data revealed 50 year intervals of increased fire frequency that recurred

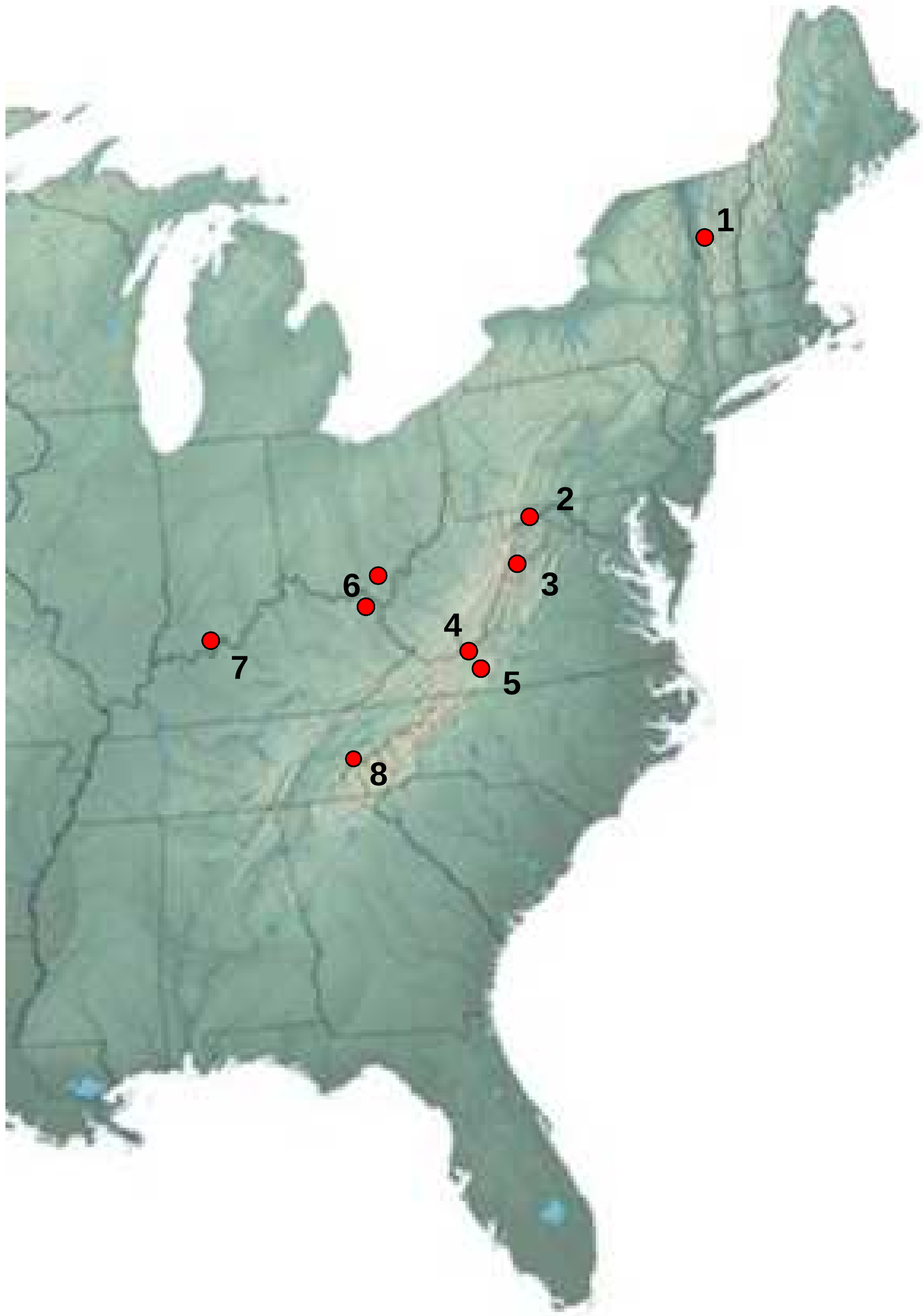

Figure 1.1 Locations of previously published fire history studies in eastern North America. (1) Mann *et al.*, 1994; (2) Shumway *et al.*, 2001; (3) Schuler & McClain, 2003; (4) Hoss *et al.*, 2008; (5) Sutherland *et al.*, 1995; (6) McEwan *et al.*, 2007; (7) Guyette *et al.*, 2003 (8) Harmon, 1982.

every 100–200 years and coincided with increased fuel accumulation and summer drought. Although the fire-intervals reported here were not derived by standard dendroecological methods, this study is notable in that it highlights a long history of relatively frequent fire in an area of New England where fire is generally not accepted as an important component of forest dynamics (see Table 1.1).

Investigations of relationships between fire and anthropogenic activity in oak barrens of southern Indiana (Fig. 1.1; Guyette *et al.,* 2003) reveal a frequent fire regime (Table 1.1) and suggest that the temporal variability of the regime was closely associated with changes in human population density, settlement patterns and migration. For example, a particularly long fire-free interval in the early portion of the record corresponded with emigration of Native American populations from the region. Conversely, increasing fire frequency during the latter half of the record was attributed to European settlement along the Ohio River (Guyette *et al.,* 2003). It is important to note that in this study, the authors derived fire-intervals by standard dendroecological techniques, but also included the pith-to-first scar as a fire interval, which could inflate the length of the fire-free interval.

Two fire history studies conducted in oak stands of Maryland and West Virginia revealed fire-intervals of 7.6–17.1 years (Fig. 1.1; Table 1.1; Shumway *et al.,* 2001; Schuler & McClain, 2003). Harmon (1982) collected 43 cross sections from 26 stands in a 9100 ha area of the western portion of the Great Smoky Mountain National Park (Fig. 1.1). Harmon's study revealed that fire occurred across various topographic positions (e.g. aspect, slope, elevation) of the study area at an average interval of 12.7 years, with greatest frequency at lower elevations (see Table 1.1).

Table 1.1. List of published fire history studies in the eastern United States. Studies marked with one asterisk indicate fire-intervals derived using non-standard dendroecological protocols. Studies marked with two asterisks contained multiple study sites, each with relatively few fire-scarred samples. The data reported in the Sample Size column reflect total specimens collected.

	Fire History Study	Location	Sample Size	Length of Chronology	Fire Interval(s) (Years)
1	*Mann *et al.*, 1994	Vermont	32	1504–1851	18.3±14.4
2	Shumway *et al.*, 2001	Maryland	20	1615–1958	7.6
3	Schuler & McClain, 2003	West Virginia	17	1895–2002	14.8–17.1
4	Hoss *et al.*, 2008	Virginia	73	1765–1993	2.2–18.4
5	Sutherland *et al.*, 1995	Virginia	14	1895–2002	9–11
6	**McEwan *et al.*, 2007	Ohio, Kentucky	225	1875–1954	2.1–12.2
7	*Guyette *et al.*, 2003	Indiana	27	1656–1992	8.4
8	Harmon, 1982	North Carolina, Tennessee	43	1856–1940	12.7

Recent work by McEwan *et al.* (2007) in mixed-oak forests of the Allegheny and Cumberland Plateaus (Fig. 1.1) report mean fire intervals over a 67-year period ranging from 2 to 12.2 years (Table 1.1). This study encompassed nine study sites within a 240 km latitudinal gradient. Fire was widespread and frequent throughout the study area and played an important role in the establishment and development of the current mixed-oak overstory (McEwan *et al.*, 2007).

Two fire-history studies are particularly important for elucidating fire-regimes of the Appalachian region. In two Table Mountain pine stands on Brush Mountain, Virginia (Fig 1.1), Sutherland *et al.*, (1995) reported that fires burned approximately every 10 years (see Table 1.1). Stand age structure revealed the establishment of two distinct cohorts whose establishment dates coincided with major fire events. This was a small study conducted during the 1995 North American Dendroecological Fieldweek (NADEF) and was the forerunner of my dissertation research.

Hoss *et al.*, (2008) investigated the fire-history of an oak-dominated forest on Peters Mountain, in Giles County, Virginia (Fig. 1.1). Fire-intervals ranged from 2–18 years (see Table 1.1) and exhibited little temporal variability regardless of increasing anthropogenic activity in the area. Despite the number of specimens collected (73), some fires were only recorded by a few trees indicating the occurrence of small-extent fires; however, there was evidence of larger, more widespread fires that occurred at longer intervals (11–13 years). The results of age structure analysis indicated that the establishment and maintenance of the dominant tree species is directly related to the fire frequency at the site. These findings are particularly important because they are consistent with the fire-oak hypothesis (Abrams, 1992) that states historically, oaks were perpetuated by fire. In addition to providing information about historic fire frequency, the studies by Sutherland *et al.* (1995) and Hoss *et al.* (2008) also reveal the influence of modern fire suppression on species composition and structure by demonstrating that relatively shade-tolerant, but fire-intolerant, tree species encroached after the cessation of frequent burning.

Some chronologies (e.g. Harmon, 1982; Schuler & McClain 2003; McEwan *et al.*, 2007) are restricted to the post-settlement era (mid- or late-19th to 20th centuries); however they provide valuable information about the role of fire and changing land use on forests that were believed to have originated during this period (Aldrich *et al.*, 2010). The role of fire prior to the period of capital intensive logging and mining is less clear, but is important because resource managers commonly use presettlement conditions as baseline conditions for restoration targets (Aldrich *et al.* 2010). Chronologies reported by Mann *et al.*, (1994), Shumway *et al.* (2001) and Guyette *et al.*, (2003) extend fire history research beyond the presettlement era, but it is clear that more extensive investigations of fire history are needed if past fire regimes of the Appalachian region are to be characterized adequately.

Purpose of the Study

In this study, I use dendroecological techniques to investigate fire history and vegetation dynamics of mixed pine-oak forests in the central Appalachian Mountains of Virginia. The study addresses three main objectives: (A) develop a lengthy fire chronology to document fire history beginning in the late presettlement era and extending throughout the period of European settlement, industrialization and modern fire exclusion; (B) explore fire-climate relationships; and (C) investigate vegetation dynamics in relation to fire occurrence.

Fire History

Human land use is thought to have exerted a strong control on fire regimes of temperate forests (Pyne, 1982; Delcourt *et al.*, 1986; Abrams, 1992; Lynch & Clark, 2002; Guyette *et al.*, 2002; Aldrich *et al.*, 2010). These forests have been affected heavily by agricultural clearing, settlement, mining, logging, fire protection and other human influences (Williams, 1998; Nowacki & Abrams, 2008). Pyne (1982) argued that European forests burned frequently under extensive human land uses such as agricultural expansion, but declined with shifts to intensive sedentary agriculture and industrial forestry. Until recently, however, the history and role of fire in eastern North American forests received relatively little attention (Brose *et al.*, 2001). Consequently, past fire regimes are not well known, particularly for periods before the late 1800s. I address the following questions to investigate the fire history of three central Appalachian Mountain landscapes through multiple land use episodes:

A. How common were fires on the presettlement landscape?
B. Did the frequency of fire rise as the extent of human land use increased from presettlement to early European settlement to widespread extractive industrial activities (iron mining/smelting and logging)?
C. Did the frequency of fire decline in association with fire protection during the 20th century?

Fire-climate Interactions

Climate influences fire activity by controlling fuel accumulation and moisture content (Kitzberger *et al.*, 1997; Lafon *et al.*, 2005). Investigations of the short- and long-term fluctuations in climate and variations in fire activity demonstrate that climate strongly influences patterns of burning (Lafon *et al.* 2005). In many dry forests and shrublands of the western US, fire activity is greatest when unusually wet years that promote the accumulation of fine fuels are followed by subsequent drought (Kitzberger *et al.*, 1997; Grissino-Mayer *et al.*, 2004; Lafon *et al.* 2005).

In more humid climates, wet periods prior to the year of drought may not be necessary for the accumulation of fine fuels because wetter conditions support heavy fuel loads every year (Kitzberger *et al.* 1997; Lafon *et al.*, 2005). In these environments, drought during the year of fire may to be the climatic factor of most significance, particularly for fire episodes in which multiple fires burn synchronously throughout a region (Lafon *et al.*, 2005).

Here, I investigate relationships between interannual variations in fire activity and climatic variability. I use Superposed Epoch Analysis (SEA) to address the following questions:

(1) Are interannual variations in fire activity related to climatic cycles of wetness and drought?

(2) Do region-wide fire episodes, recorded at multiple study sites, coincide with drought years?

Vegetation Dynamics

It is increasingly recognized that many presettlement forests in the eastern US were influenced by a fire regime that resulted in vegetation types dependent on frequent burning for regeneration and maintenance (van Lear & Waldrop, 1989; Frost, 1998; Elliott *et al.*, 1999; van Lear, 2004; Brose *et al.*, 2005). This region has a high diversity of species with a wide range of strategies for persisting under different disturbance regimes, including fire (Nowacki & Abrams, 2008). It is generally accepted that widespread and prolonged fire exclusion has led to unprecedented ecological changes in fire-adapted ecosystems (Nowacki & Abrams, 2008), and many studies have documented these changes (Heinselman, 1973; Abrams & Nowacki, 1992; Wolf, 2004; DeWeese, 2007; Hoss *et al.*, 2008; Aldrich *et al.*, 2010). Modern forests are denser than presettlement forests and increased shading has favored the establishment of an abundance of shade-tolerant, fire-sensitive plants. Nowacki & Abrams (2008) hypothesize that over time, these species create cooler, wetter, and less flammable microenvironmental conditions that continually favor mesophytic species over xerophytic species. The documented shift in fire regimes resulting from fire control practices in the 20th century offers an opportunity to investigate the role of fire in controlling vegetation composition and structure under contrasting fire regimes. Specifically I ask:

(1) How do the dominant tree species (pine and oak) with different persistence strategies (e.g. fire resistance via thick bark; resilience via sprouting) respond to changes in fire regimes?

(2) In the absence of fire, is there an observed shift from fire-resistant, xerophytic trees to a community with a high diversity of mesophytic trees and shrubs?

Organization of Dissertation

This dissertation consists of six chapters. Chapter II is the literature review structured around the main objectives of the study. In it, I first summarize what is known about anthropogenic activity on historic fire regimes from the Archaic Period (8000–2800 BP) through the early 20th century. Second, I provide a discussion on basic relationships between fire and climate then compare and contrast what is known about fire-climate interactions in the western US with what is known in the eastern US. The final portion of this chapter highlights the ecological role of fire on vegetation community function and structure in the context of plant persistence strategies and species diversity. Chapter III describes the physical setting of the study area as well as land use history specific to each study site. This chapter also delineates the field, laboratory and statistical methods used in this study. Chapter IV provides the results of the study, and Chapter V discusses these findings in the context of fire history, fire-climate interactions and vegetation dynamics. Chapter VI sets forth my conclusions and their implications for resource management and future research.

CHAPTER II

REVIEW OF LITERATURE

Anthropogenic Influence on Fire Regimes in Eastern North America

American Indians

Indians in the eastern US burned for a variety of reasons. The frequency, intensity and location of burning varied spatially and temporally depending on what resources were being managed (Moeller, 1996; Fritz, 2000; Hammett, 1992). It is believed the earliest hunter-gathers (12500–9500 BP) in North America used fire primarily for hunting megafauna (mastodon, bison and caribou), but they also may have used fire to clear the forest understory to facilitate nut collecting and the growth of pioneer plant species (Bonnicksen, 2000; Fowler & Konopik, 2007; Nowacki & Abrams, 2008).

During the Archaic Period (8000–2800 BP), Indians probably used fire to create a variety of habitats to attract game; create ecotones that appealed to white-tailed deer (*Odocoileus virginianus*) (Delcourt *et al.*, 1986); maintain open woodlands and savannas for early-successional wildlife species (Brose *et al.*, 2001). Fire was also important in maintaining the prairies that sustained great herds of American bison (*Bison bison*) (Lorimer, 2001). Low-intensity fires were used to facilitate hunting by driving or encircling game (Brose *et al.*, 2001; Abrams & Nowacki, 2008).

The Woodland (2800–1300 BP) and Mississippian (1300–400 BP) Periods were characterized by a mixture of agricultural and hunter–gather societies (Woodcock &

Wells, 1994). The cultural transition from mobile, hunting–gathering groups to settled communities that relied more heavily on plants as foodstuffs prompted modifications in the use of fire as a management tool (Woodcock & Wells, 1994; Fowler & Konopik, 2007). Growing populations required more and more land to be cleared for villages, political centers and agricultural fields. Fire was likely used to prepare planting sites for agriculture, maintain habitats for mast and fruit producing trees and prepare seedbeds for domesticated species (Fowler & Konopik, 2007; Abrams & Nowacki, 2008).

There is general agreement about the use of fire by American Indians prior to European contact; however, considerable uncertainty still exists about the extent to which this use altered the North American landscape (Pyne, 1982; Russell, 1983; Loope & Anderton, 1998; Patterson & Sassaman, 1988; Denevan, 1992; Clark & Royall, 1996; Bonnicksen, 2000). Early scholars and popular writers portrayed pre-Columbian North America as a “wild” or “pristine” landscape largely untouched by human hands (Butzer, 1992; Denevan, 1992; McCann, 1999). Under this scenario, American Indians were described as “environmentally unobtrusive” (Moeller, 1996), living in harmony with nature (Butzer, 1992; Briggs *et al.* 2006). More recently, however, this idea has been challenged in a growing body of historical, anthropological, and paleoecological evidence that suggests that Indian use of fire had more widespread impacts on the landscape than previously thought (Day, 1953; Pyne, 1982; Patterson & Sassaman, 1988; Denevan, 1992; McCann, 1999; Bonnicksen, 2000; Keeley, 2002; Williams, 2002; Briggs *et al.*. 2006; Kay, 2007).

A combination of direct (historical records) and indirect (archeological, paleoecological) methods can be used to help evaluate the impact of American Indians (Meyers & Peroni, 1983; Russell, 1983; Patterson & Sassaman, 1988; Briggs *et al.*, 2006; Fowler & Konopik, 2007). Historical documents written by early European explorers provide important descriptions of Native American landscapes (Hammett, 1992). The information gleaned from these texts describes a mosaic of vegetation types and suggests that aboriginal burning practices may have influenced ecosystems to various degrees not only in the eastern US but other regions of North America as well (Hammett, 1992; Parshall & Foster, 2002; Fowler & Konopik, 2007). Many of these writings mention fire directly. For example, William Bartram (1791), describing his time spent with the Creek Indians in Florida, noted the appearance of great vultures that "seldom appear but when the deserts are set on fire (which happens almost every day throughout the year, in some part or other, by the Indians, for the purpose of rousing the game, as also by the lightning)". In this passage, the term "deserts" is used to describe a wilderness or deserted place (in this case, grassland or savanna) as Bartram continues his narrative "when they are seen at a distance soaring on the wing, gathering from every quarter, and gradually approaching the burnt plains, where they alight upon the ground yet smoking with hot embers; they gather up the roasted serpents, frogs and lizards; filling their sacks with them". Others provide indirect evidence of fire in their description of landscapes that may have been maintained by fire (Fowler & Konopik, 2007). For example, Garcilaso de la Vega, a member of the De Soto Expedition to North America in the 16th century, writes that they saw "a great quantity of oaks and extensive grazing lands" on their five day journey from the northwest corner of South Carolina over the mountains into the Tennessee River Valley (Rostlund, 1957).

Despite many written accounts describing widespread Indian use of fire, Emily Russell (1983) concluded that no strong evidence exists to suggest that Indians purposely burned large areas of the landscape creating the open woods observed by early European travelers. Russell (1983) maintained that there is little direct historic evidence to support the case for widespread aboriginal burning, and that the existing accounts are either unreliable or unspecific in location and/or extent of Indian burning. She further contends that some writers' motives may have been biased toward economic or religious self-interests (Russell, 1983).

Myers & Peroni (1983) argue that historical documents have limited applicability when used as the sole resource in determining aboriginal fire patterns and that drawing conclusions from these documents alone ignores a large body of both archeological and ecological literature illustrating global use of fire by aboriginals. Archeological data can provide the depth of time necessary to explore relationships between human land use and ecosystem structure beyond the bounds of written historical documents (Meyers & Peroni, 1983; Briggs *et al.*, 2006).

Archeological data are used to reconstruct the physical setting and cultural histories of past civilizations. Plant and animal macro-remains (e.g. seeds, charcoal, plant food debris, bones, fish scales and exoskeletons) found at excavation sites are used to document population locations and densities, and concomitant shifts in subsistence patterns that can influence vegetation patterns and fire regimes (Myers & Peroni, 1983).

For example, the excavation of a complex of interconnected rockshelters in eastern Kentucky revealed diagnostic artifacts (projectile points and pottery shards) dating from the Middle Archaic through Late Woodland Period that document an 8000 year occupational history of the area (Delcourt *et al.*, 1998). Ethnobotanical remains retrieved from the sites indicate the occupants practiced animal husbandry and domestication of native plants during the latter portion of occupation (Delcourt *et al.*, 1998).

In addition to archeological data, paleoecological methods (pollen and charcoal analysis) can provide the range of spatial and temporal resolution to help elucidate the role of aboriginals in influencing the composition and structure of vegetation on the pre-Columbian landscape (Russell *et al.*, 1993; Clark *et al.*, 1996; Delcourt & Delcourt, 1998; Foster *et al.*, 2002). Lynch & Clark (2002) used pollen and charcoal analyses to assess long-term fire-vegetation patterns and examine the effects of Indian and European settlement on forests of the Appalachian Mountain regions of Maryland, Virginia and North Carolina. Over the past 20000 years, accumulation of charcoal at all sites confirmed that fire was present on the landscape, but its ecological role and importance varied among sites and throughout time. The heterogeneity of fire in these forests indicates that fire as a disturbance agent was discontinuous, and may at times have facilitated the dominance of oak. Charcoal accumulation increased at all study sites after European settlement, underscoring the importance of fire as a disturbance factor during this time. At some sites, the increase occurred during the shift from forest to pasture in the late 18th and 19th centuries, while at other sites, fire was more important during the logging period of the 1880s to 1920s (Lynch & Clark, 2002).

In the southern Appalachian Mountains, Delcourt & Delcourt (1997; 1998) and Delcourt *et al.* (1998) used paleoecological and archeological data to evaluate the importance of human impacts on vegetation over the past 3000 years. Increases in local fire frequency corresponded with changes in Native American activities from hunting and gathering toward a more agrarian lifestyle. Delcourt & Delcourt (1997) argued that these activities created and maintained a heterogeneous mosaic of different vegetation types across the landscape, including oak and chestnut forests in the uplands, fire-adapted pine on ridge tops and disturbance-adapted hardwoods occupying abandoned agricultural fields (see also Hammett, 1992). The temporal concurrence of pre-Columbian occupation, domestication of native plants and increased fire activity underscores the importance of aboriginal activities in structuring vegetation composition in the region, especially considering that lightning ignitions are relatively infrequent in the Appalachian Mountains (Delcourt & Delcourt, 1998; Kay, 2007; Abrams & Nowacki, 2008).

It is becoming more accepted that in many areas, frequent, low-intensity fires were important in structuring plant communities (Kay, 2007), and few deny the historical relationship between humans and fire (Brose *et al.*, 2001; Abrams & Nowacki, 2008). It is the contention of many, however, that the importance of Native American burning varied over time and space (Hammett, 1992; Foster *et al.*, 2002). For example, in New England, Parshall & Foster (2002) collected paleoecological data from 18 lakes across the region, representing a variety of vegetation types and landforms, to reconstruct the past distribution of fire and to investigate the possible drivers of fire activity. The authors maintain that the major factor influencing the distribution of fire across the region was climate, particularly the number of growing degree days. Other factors that may have exerted control over local fire regimes included landforms, firebreaks and prevailing winds. The distribution of presettlement fire broadly corresponded with Native American populations, with higher fire activity corresponding to higher population sizes along the coast and inland waterways, although there is no evidence to support the assertion that intentional burning by American Indians affected the distribution of vegetation across New England (Parshall & Foster, 2002).

Keeley (2002) evaluated the importance of aboriginal burning on vegetation distribution in the coastal ranges of central and southern California. Historically, the coastal ranges of California were regions of high Indian populations and low frequency of lightning-ignited fires. The landscape was dominated by shrubs that offered few resources for humans, and natural fire frequencies were inadequate to maintain a more habitable environment. Keeley hypothesized that Native American burning was necessary to supplement the natural fire regime, allowing for the creation of a landscape bearing a mixture of shrubland and grasslands.

Vale (1998, 2000) argued that large portions of North America were relatively unaffected by aboriginal burning during the presettlement period and that in drier regions of the American West, fire regimes were dominated by lightning-ignited fires. He claims any additional burning done by Indians probably altered vegetation only in the immediate vicinity of villages, but did not affect the regional landscape. He does concede, however, that aboriginal burning was probably more important in the more humid eastern portions of the continent where lightning ignitions are less important (Vale, 2000).

Kay (2007) and others (Sauer, 1950; Day, 1953; Lorimer, 2001; Keeley, 2002) cite several ecological examples that suggest aboriginal burning not only structured a wide range of plant communities all across North America, but created many of the vegetation associations once thought to be natural. Some of the most compelling evidence comes from the temperate forests in the eastern United States (Kay, 2007). During the past 8000– 10000 years, much of this region was dominated by fire-tolerant, early- to mid-successional species such as oaks, chestnut and pine. Since European settlement and subsequent reduction in fire frequency, these species have been replaced by late-successional, fire-intolerant trees such as black gum and maple.

European Settlers

Brose *et al.* (2001) argued that the cultural transition from aboriginal habitation to European settlement (mid 1500s–early1700s) did little to alter the regime of frequent, low-intensity fires because early settlers adopted the Indian model of burning, thus preserving the historical fire regime. A few writers, however, contend that during this transitory period, the decline of Native American populations significantly decreased the frequency of burning. Subsequently, many of the open, park-like landscapes created and maintained by Indian burning returned to a more forested landscape (Denevan, 1992; Williams, 2002; Fowler & Konopik, 2007; Hicks, 2000).

Initially, European settlement progressed slowly. By 1638, only about 30000 Europeans occupied North America (Denevan, 1992). By 1750, there were approximately 1.3 million Europeans, mainly occupying the coastal area from New England to northern Florida (Denevan, 1992). Westward progress was relatively slow into the 1700s due to the lack of efficient region-wide transportation systems (Denevan, 1992; Hicks, 2000).

In the central and southern Appalachian Mountains, European settlement began in the early- to mid-1700s in the Shenandoah Valley, and settlement farther from the main valleys occurred in the late 1700s (Williams, 1998). Many early settlers were subsistence farmers, their burning practices a combination of European traditions and techniques learned from American Indians (Pyne, 1982; Hicks, 2000). As with their predecessors, settlers' use of fire probably varied from place to place, depending on the desired management effect (Hammett, 1992). Initially, human impacts were concentrated along waterways and in valleys, but between 1750 and 1850, increasing population pressure forced the expansion of agricultural and timber harvesting activities into more remote areas (Denevan, 1992).

The era of extractive industrial activity (1850–1930) had extensive logging and mining activity that probably led to a marked increase in fire frequency and intensity over much of the Appalachian region (Harmon, 1982; Williams & Johnson, 1990; Abrams & Nowacki, 1992; Williams, 1998; Brose *et al.* 2001; Schuler & McClain, 2003). The development of extensive railroad systems facilitated logging in areas previously inaccessible due to steep terrain. Commercial logging practices were highly destructive, resulting in widespread erosion on steep sites. The dried slash, or left-over logging debris, provided fuel for wide-spread, intense fires. The steam engines that powered the locomotives were a primary ignition source, especially during periods of drought (Pyne, 1982; Williams, 1998; Brose *et al.,* 2001; Fowler & Konopik, 2007).

In response to the widespread destruction of eastern forests due to massive wildfires, Gifford Pinchot, founder of the United States Forest Service (USFS), led a nationwide conservation effort to identify wildfire as an undesirable, destructive force that must be controlled (Brose *et al.*, 2001). The Weeks Act of 1911 established federal forests under the supervision of the newly created USFS, and fire prevention became a top priority (Brose *et al.*, 2001). Fire-prevention legislation also created fire wardens at state and local levels in addition to nationwide education efforts to inform the public about the danger and prevention of wildfire (Brose *et al.*, 2001). The Smokey Bear anti-fire campaign instituted in 1944 became one of the most influential advertising campaigns in history, educating generations of Americans of the dangers of wildfire (Brose *et al.*, 2001). Early fire prevention efforts were so successful that between 1930 and 1960 the total area consumed by fire decreased from 50 million acres to about 5 million acres (Brose *et al.*, 2001).

The elimination of frequent, high-intensity fires that characterized the industrial era allowed for the development of hardwood forests, which previously were constrained by frequent and/or severe fire. Management practices were unfavorable to xerophytic pine and oak forests that rely on the frequent occurrence of fire for regeneration and maintenance (Whittaker, 1956; Zobel, 1969; Abrams, 1992; Agee, 1998; Brose *et al*., 2001). As a result, there have been considerable changes in canopy composition and structure in many eastern forests as the abundance of fire-tolerant pine and oak species declined and fire-sensitive hardwood trees and shrubs flourished (Harmon, 1982; van Lear & Waldrop, 1989; Abrams, 1992; Sutherland *et al.*, 1995; Harrod *et al.*, 1998; Williams, 1998). For example, Harmon (1982) reported that xeric slopes and ridges in western portions of the Great Smoky Mountains National Park experienced a frequent fire rotation (10–40 years) between 1856 and 1940. Because of changing land use prior to establishment of the park in 1934 and the beginning of fire suppression activities in the 1940s, fire rotation increased to over 2000 years. Consequently, between the 1930s and 1990s, mean density and basal area of canopy trees doubled, abundance of shade-intolerant trees such as pines and oaks declined, and shade-tolerant species increased (Harrod *et al.*, 2000).

Fire-climate Interactions

Fire regimes (i.e. established patterns of frequency, intensity, severity, and seasonality) in any given area are partly a function of interactions among climate-related factors, such as fuel production, fuel moisture, ignition frequency and short-term weather patterns (Grissino-Mayer & Swetnam, 2000; Lafon *et al.*, 2005; Bond & Keeley, 2005). Long-term climate affects fuel accumulation by influencing primary productivity and decomposition, while short-term weather patterns such as daily variations in precipitation, temperature, humidity and wind affect fuel moisture and fire spread (Lafon *et al.*, 2005; Petersen & Drewa, 2006; Meyn *et al.*, 2007).

In North America, a growing interest in recreating historic fire regimes and understanding the drivers of wildland fire have led to a number of studies on fire-climate relationships. Many of these studies have focused on regions in the western US (e.g. Grissino-Mayer & Swetnam, 2000; Heyerdahl *et al.*, 2001; Brown, 2006), although a few have investigated eastern North America - e.g. Florida (Prestemon *et al.*, 2002), Mississippi (Dixon *et al.*, 2008) and the central Appalachian Mountains (Lafon *et al.*, 2005; Lafon & Grissino-Mayer, 2007). These investigations reveal that patterns of burning are strongly influenced by climate, even in areas where fire regimes were historically dominated by anthropogenic ignitions (Lafon *et al.*; 2005). Recent studies have revealed some general patterns of fire-climate relationships (e.g. Baker, 2003; Schoennagel *et al.,* 2004; Meyn *et al.,* 2007; Littell *et al.*, 2009): (1) in humid climates, fuel moisture is the primary limitation on fire ignition and spread, thus fire activity is most extensive during periods of drought; 2) in dry climates fire activity is often highest when drought years follow unusually wet years that promote the accumulation of fine fuels; and (3) oscillations between wet years that promote fuel production, and dry years that favor burning.

In the humid Southeast, fire-climate relationships are not as well documented as in the western US, but existing studies indicate that the relationships seem to follow the first pattern, i.e., wet periods prior to the year of drought may not be necessary for the accumulation of fine fuels because wetter conditions support heavy fuel loads every year. In these environments, drought during the year of fire may to be the climatic factor of most significance, particularly for fire episodes in which multiple fires burn synchronously throughout a region (Lafon *et al.*, 2005). Fire history studies on drier sites in the Appalachian Mountains (Harmon, 1982; Sutherland *et al.*, 1995; Shumway *et al.*, 2001; Armbrister, 2002; Schuler & McClain, 2003) suggest that historically, surface fires burned at intervals of about 5–15 years, and many appear to have been associated with drought (Lafon *et al.*, 2005).

Lafon *et al.* (2005) used records of wildland fire during 1970–2003 to examine contemporary fire-climate relations in the central Appalachian Mountains. Of particular interest to my study are findings related to seasonal patterns of fire occurrence and interannual variations in fire activity with respect to climatic cycles of wetness and drought. The study found that the occurrence of fire varies seasonally with weather and fuel conditions. Fire activity is highest during fall and spring and lowest during the winter and summer months. Fall burning coincides with the peak of fine fuel accumulation and optimal weather conditions that are more conducive for fire activity (i.e. low precipitation, high temperatures, high winds and low humidity). Human ignitions are more important during this time of year because of reduced thunderstorm and lightning activity in the region (Lafon *et al.*, 2005). Cold temperatures during the winter months prevent the decay of fine fuels on the landscape, thus providing ample fuel for burning with the return of warmer temperatures and increased thunderstorm activity in the spring. Although lightning ignitions peak during late spring and early summer, the increased moisture content of new vegetative growth, higher humidity levels and declining wind speed suppresses fire activity (Lafon *et al.*, 2005).

The identification of seasonal patterns of fire activity has important implications for interpreting dendroecological analysis of fire history studies. For example, in two Table Mountain pine stands in Western Virginia, Sutherland *et al.* (1995) found that most fires that occurred during the period of study (1798–1944) were dormant-season burns that occurred either during the spring or fall. While it is not possible to identify the ignition source through dendroecological techniques, it can be inferred from the seasonality of the burns that most of the fires were probably ignited by humans (Lafon *et al.*, 2005).

Fire activity also varied annually, both in terms of anthropogenic and natural ignitions, which was shown to be related to variations in climate. For example, spring anthropogenic fire activity was highest during years with a dry winter and spring. For natural fires, dry conditions were important throughout the year, especially late spring and summer. On the other hand, fall anthropogenic fire activity was related to summer and fall moisture levels (Lafon *et al.*, 2005).

Vegetation Dynamics

Many environmental factors influence the structure, composition and functioning of plant communities. Over the past 50 years, the recognition of fire as an evolutionary force in forest ecosystems has been increasing (Attiwill, 1994). Likewise, the use of plant functional traits as a method of assessing vegetation responses to fire as a disturbance has become more prevalent (Diaz *et al.*, 1999). Vegetation communities that have evolved with a long history of disturbance exhibit certain morphological and physiological characteristics that enable them to persist, compete, and regenerate under specific disturbance regimes (Diaz *et al.*,1999; Pausas *et al.*, 2004) and many have several features in common (Grime, 1977). The most common of these traits is the tendency for certain plants to complete their lifecycles relatively quickly (i.e. annual, bi-annual or short-lived perennials) to take advantage of intermittent opportunities for favorable growth. In these plants, a large proportion of energy is directed into copious seed production, instead of vegetative development, increasing the likelihood of reproduction before the next disturbance occurs. Another common characteristic is the ability of seeds to remain viable in the soil for long periods and germinate rapidly when exposed to light or high temperatures (Grime, 1977).

Noble & Slatyer (1980) developed qualitative models of vegetation dynamics for communities subject to recurrent disturbance. These models are based on vital attributes, or life history traits defined relative to specific disturbance types. Three main groups of vital attributes were identified: (1) the method of species arrival or persistence at the site during and after the disturbance; (2) the ability to establish and grow to maturity following a disturbance event; and (3) the time taken for the species to reach critical life stages.

Rowe (1983) incorporated portions of Noble & Slatyer's vital attribute models in a characterization of plant adaptations to fire. However, in Rowe's conceptualization, traits favoring invasion, seed storage, and regrowth are more important in fire-prone areas than those favoring competition. This is especially important in environments that experience frequent disturbance, because competition between species may not have adequate time to develop before another disturbance occurs (Lloret *et al.*, 2005).

In Rowe's (1983) assessment, vegetation responses to fire are classified according to their 'mode of persistence'. Two broad categories are identified based on the primary mode of propagation (i.e., disseminule-based or vegetative-based) and further demarcated by mode of regeneration and fire-tolerance characteristics. According to this model, plants with disseminule-based strategies are identified as ‘invaders’, ‘evaders’ or avoiders’. Invaders are characterized by their ability to produce large numbers of short-lived propagules that quickly invade an area following fire. These species are shade-intolerant and exhibit rapid growth. Evaders have relatively long-lived propagules that are either stored in the canopy or lie dormant in the soil until triggered to germinate by high temperatures. Evaders fall into two distinct categories; shade-intolerant, early-successional ephemerals (annuals, bi-annuals) and semi-tolerant to shade-tolerant perennials that can persist into later successional stages, thus contributing to the seed bank for longer periods. Avoiders are late-successional, shade-tolerant species that exhibit few adaptations to fire and are important components of more mesic ecosystems dominated by long fire cycles. Some avoiders require modification of the ecosystem (humus accumulation or shade) before they can invade and colonize an area.

Plants that persist vegetatively under burning are classified as either ‘resisters’ or ‘endurers’. Resisters are species whose above-ground parts can survive low-severity fires. Many members of the genus *Pinus* exhibit fire-resistant characteristics that protect against surface fire (thick bark) and reduce the likelihood that fire will reach the canopy (self-pruning branches) (Schwilk & Ackerly, 2001). Endurers are plants whose underground parts survive fire and regenerate from stem bases, roots, or rhizomes. These species can possess either shade-intolerant or tolerant characteristics. The shade-intolerant members of this group are early-successional species that require recurrent fire for regeneration and maintenance. Shade-tolerant members of this group are able to persist in the absence of disturbance. Endurers are differentiated from tolerant-sprouting avoiders in that they establish immediately after a fire. In contrast, tolerant-sprouting avoiders establish later in the successional sequence (Rowe, 1983).

It is important to note that some species may exhibit more than one persistence strategy, thus may not fit exclusively into any one of the five categories (Rowe, 1983). For example, in a study comparing characteristics and recovery rates of tundra vegetation following fire in northwestern Alaska, Racine *et al.* (1987) found it difficult to place bluejoint grass (*Calamagrostis canadensis)* and fireweed (*Chamerion angustifolium)* into a single category because plants exhibiting both disseminule-based and vegetative-based forms of propagation were found on burned areas following fire. Recognition that various combinations of plant functional traits can lead to differential success under changing fire histories may have important implications for long-term vegetation dynamics (Pausas *et al.*, 2004).

In ecosystems with a long history of frequent fire, slight alterations in the fire regime may only lead to minor changes in relative abundance of the dominant tree species. However, if the fire regime is drastically altered, it is likely that some species with strategies that allow them to persist in fire-prone areas will be filtered out and others with different persistence strategies would be able to establish and thrive (Diaz *et al.*, 1999).

Nowacki & Abrams (2008) hypothesized that the abrupt and enduring shift in fire regimes in the early 20th century has led to a number of ecological changes in fire-prone ecosystems throughout the US. In the absence of fire, environmental conditions in closed-canopy forests have shifted to favor shade-tolerant, fire-sensitive, mesic species over their xerophytic, fire-adapted competitors. Over time, 'mesophication' (the escalation of mesic, microenvironmental conditions; Nowacki & Abrams, 2008) impedes fire activity by producing dense shading that promotes moist, cool microclimates and fuels not conducive to burning. This cycle is reinforced by positive feedback loops that sustain environmental conditions impeding the establishment and regeneration of fire-dependent species.

The theory of alternative stable states provides a good framework for characterizing the mesophication process (Nowacki & Abrams 2008). According to this theory, a community may exist in a number of different locally stable states until a disturbance event triggers a switch to a new stable state. In fire-adapted ecosystems, much of the vegetation is so dependent on periodic fire that the absence of fire may be the perturbation that causes a change in states (Nowacki & Abrams, 2008). For example, periodic fire apparently maintained the tallgrass prairies of North America for millennia (Sauer, 1950; Evans *et al.*, 1989; Collins, 1990), however, long-term fire suppression transformed much of the once continuous prairies to deciduous forests and now only scattered remnants remain (Evans *et al.* 1989; Bock & Bock, 1998).

The shift in species composition from xerophytic, shade-intolerant species to shade-tolerant, fire-sensitive species in the absence of fire occurs more rapidly on more productive sites (Smith & Huston, 1989; Nowacki & Abrams, 2008). On less productive, xeric sites, the shift to mesophytic communities occurs more slowly because mesophytic species cannot easily invade dry sites (Nowacki & Abrams, 2008).

In the mixed oak-pine forests of the eastern US, xerophytic oak and pine species are increasingly being replaced by late-successional mesophytic species such as red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), beech (*Fagus* spp.), and blackgum (*Nyssa sylvatica*) (Abrams, 1992; Brose *et al.*, 2001). As stand density increases and the understory becomes more shaded, insolation and wind speeds decrease, and relative humidity increases resulting in a cooler and moister understory. These conditions, coupled with less flammable leaf litter of mesophytic species, limit fire activity and intensify the mesophication process. In many of these communities, stand-level tree diversity has increased, at least temporarily, as previously fire-restricted tree species have recruited into the canopy. However, as xerophytic species are increasingly excluded through gap-phase replacement, it is possible that overall tree species diversity will decline and forests will move toward dominance by a few highly shade-tolerant species (Loehle, 2000, Nowacki & Abrams 2008).

CHAPTER III

METHODS[*]

Study Area

Topography and Soils

The study was conducted in the George Washington National Forest (GWNF), located in portions of the Ridge and Valley and the northern Blue Ridge physiographic provinces of Virginia. The Ridge and Valley is characterized by a series of parallel, folded and faulted, narrow ridges that rise above the intervening valleys. Most of the Ridge and Valley lies at elevations below 900 m (3000 ft); but elevations of the ridges rise to elevations of 1200–1400 m (4000–4600 ft) (McNab & Avers, 1994; Fleming *et al.*, 2006).

Shallow, rocky soils are typical on the steep slopes and ridges underlain by more resistant sandstone, quartzite and shale; while deep, loamy soils are found at lower elevations and coves that have substrates of less resistant limestone, dolomite and shale (Daniels, 2006). The Great Valley of Virginia is the largest limestone valley along the eastern edge of the Atlantic coast. The valley soils are composed of limestone and carbonate-rich shale that have weathered into deep productive soils. These limestone valleys support some of the most intensive row-crop and animal production agriculture

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[*] Part of this chapter is reprinted with permission from "Three centuries of fire in montane pine–oak stands on a temperate forest landscape", by Aldrich, S.R., Lafon, C.W., Grissino-Mayer, H.D., DeWeese, G.G., and Hoss, J.A. 2010. *Applied Vegetation Science*, 13: 36–46. Copyright 2010 by John Wiley and Sons.

in the Mid-Atlantic region (Daniels, 2006). The soils have a mesic temperature regime (mean annual soil temperature between 8°C and 15°C) and mostly udic moisture regime (soils anticipated to be moist within 90 days of the summer solstice and dry conditions typically do not persist for more than 60 consecutive days) (McNab & Avers 1994, Soil Survey Staff, 2010).

The Blue Ridge forms the eastern portion of Virginia's mountain region. The northern Blue Ridge (north of the Roanoke Gap) is a rugged region with steep slopes and a narrow (8–16 km; 5–10 mi) ridge (McNab & Avers, 1994). Elevation ranges from 457–1280 m (1500–4200 ft). The broad mountains of this region are characterized by narrow, irregularly weathered series of peaks underlain by resistant granites and metabasalts (McNab & Avers, 1994). The topography of the Blue Ridge varies from gentle to steep sloping side ridges and steep-sided, rugged hollows. Boulders and bedrock outcrops are common on upper slopes, but not extensive. The mountain peaks are incised by numerous gaps, saddles and wide alluvial valleys (Tolley, 1983). In general, most of the Blue Ridge is steep and rocky and not well suited for agricultural production; however, localized areas have soils that are moderately deep and of medium texture suitable for intensive forage and row-crop-based animal production (McNab & Avers 1994; Daniels 2006). The soils have a mesic temperature regime, and udic moisture regime (McNab & Avers 1994).

Climate

The central Appalachian Mountains are characterized by a humid continental climate, with pronounced seasonal variations in temperature and precipitation (Bailey, 1978). Periodic droughts and wet spells may influence fire activity on interannual time scales, while the topographic complexity of the Appalachian Mountains contributes to climatic variability that may influence fine-scale spatial patterns of fire (Lafon *et al.*, 2005). Much of the precipitation west of the Ridge and Valley is obstructed by the Allegheny Mountains while the precipitation from the east is blocked by the Blue Ridge Mountains (Fleming *et al.*, 2006). Thus, strong gradients exist between the relatively dry interior of the Ridge and Valley, with mean annual precipitation of 850–950 mm, and the Blue Ridge, where mean annual precipitation exceeds 1270 mm (Terwilliger, 1991; National Climatic Data Center, 2000, Lafon *et al.*, 2005). The region receives precipitation throughout the year, but it is more pronounced during the warmer months. In the western portions of the region, precipitation peaks during the summer months and in the Blue Ridge, in the fall (Lafon *et al.*, 2005; Lafon & Grissino-Mayer, 2007).

Vegetation

Variations in topography and climate contribute to spatial heterogeneity in vegetation in the region. Early classifications characterized much of the natural vegetation of the Ridge and Valley as oak-chestnut forests (Braun, 1950); however after the introduction of the chestnut blight (*Cryphonectria parasitica*) and subsequent decline of the American chestnut (*Castanea dentata*), oak forests came to dominate the landscape (Kuchler, 1964; Abrams, 1992; Stephenson *et al.*, 1993). These forests occupy a broad range of submesic to subxeric sites, while yellow pine stands containing pitch pine and Table Mountain pine, a fire-dependent species, are found along xeric ridge tops and west-facing slopes (Whittaker, 1956; Zobel, 1969; McNab & Avers, 1994).

Mesophytic forests are confined to ravines, coves, and high elevations (Whittaker, 1956; Zobel, 1969; McNabb & Avers, 1994; Williams, 1998).

Kuchler (1964) classified the natural vegetation of the Blue Ridge as Appalachian oak forest, southeastern spruce (*Picea* spp.)-fir (*Abies* spp.) forest and northern hardwoods. Mesophytic species such as tulip poplar (*Liriodendron tulipifera*) and red maple dominate the valleys and moist slopes. Black oak (*Quercus velutina*), white oak (*Quercus alba*), and chestnut oak (*Quercus montana*) dominate the drier mountain slopes, while pitch pine and Table Mountain pine occupy the driest, exposed ridge tops and west-facing slopes (McNab & Avers, 1994). White pine (*Pinus strobus*) is found in parts of the Blue Ridge escarpment and the Ridge and Valley. High-elevation mesic sites are occupied by northern hardwoods (e.g. sugar maple, American basswood (*Tilia americana*) and drier sites are dominated by northern red oak (*Quercus rubra*). Evergreen spruce-fir forest and associated species occur at elevations above 1800 m (5900 ft) (McNab & Avers, 1994).

Land Use History

American Indian

Archeologists have distinguished four broad phases to describe changes in Native American culture over time in the southeastern U.S. (MacCord, 1999). The Paleo-Indian (*c.* 9500 BP–*c.* 8000 BP), Archaic (*c.* 8000 BP–1000 BP) and Woodland (1000 BP–1607AD) eras all distinguish themselves with unique cultural attributes based on similarities in artifacts, subsistence, and settlement patterns (Gardner, 1981; Sarvis, 2000). The Historic Period varies according to dates of first contact with European explorers. For example in Florida, the Historic Period began with the arrival of Ponce de Leon in 1513 AD. The Historic Period in Virginia began in 1607 when European settlers arrived on Jamestown Island (MacCord, 1999).

The Paleo-Indian era was characterized by groups of nomadic people that exhibited hunter-gatherer subsistence patterns and social structure. Numerous Paleo-Indian sites are reported throughout Virginia and their size and structure vary with region. The Flint Run Complex excavated in the northern Shenandoah River valley at the boundary of the Blue Ridge and the Ridge and Valley produced a quarry-centered settlement pattern (Gardner, 1981). This complex featured four functionally different, yet interconnected site types including quarry, reduction station, base camp and maintenance camp. An additional excavation revealed a series of short-term base camps probably occupied by groups leaving or coming to the quarry complex. A similar, albeit larger, more intricate pattern of quarry-based complexes was identified in an area that extended across the Piedmont and Coastal Plain from east of the Blue Ridge to the eastern shore of the Chesapeake Bay and from northern North Carolina to the James River (Gardner, 1981). In southwestern Virginia, there is no evidence of large Paleo-Indian settlements or complex gathering places as described in northern and southeastern Virginia, but rather, data suggest that people gathered in smaller groups that traveled throughout the region (Sarvis, 2000).

During the Archaic Period, people were not as dependent on hunting as their primary means of gathering food and began to establish a less nomadic lifestyle that included the increased use of plants as a food source. Settlement patterns during the middle Archaic period (*c.* 3000 BP), became more cyclical to correspond with seasonally available resources (Sarvis, 2000). The more substantial base camps were located in the floodplains, along the foothills or interior coves and valleys of mountains. These sites were located in close proximity to river junctions and outcrops of raw materials. Smaller, more transient camps were established in the mountains and only briefly occupied in the process of moving across the upland ridges (Geier, 1981).

Toward the end of the Archaic and the beginning of the Woodland Period (c. 1000 BP) more complex settlement patterns and cultural development began to occur. Base camps and associated hunting camps and chipping stations were still common in the foothills and mountains (Geier, 1981), but decreased in number as exploitation of resources along rivers and adjacent floodplains become more important during the Early and Middle Woodland Periods **(**Gardner, 1981**).** During the Middle Woodlands Period, semi-permanent settlements sprang up on floodplains as Indians began to increasingly engage in intensive horticulture that required a more sedentary lifestyle (Gardner, 1981; MacCord, 1999). Changes in settlement and subsistence patterns during the Middle- to Late- Woodland periods, and subsequent population increases initiated profound changes in culture and society (MacCord, 1999; Sarvis, 2000). Sites reflecting Late Woodland culture are found throughout Virginia and the eastern US. These sites ranged in size from hamlets (single family dwellings) to larger, more complex excavations revealing palisaded villages. These hamlets are characteristic of settlement in the Piedmont, eastern shore of Virginia and the western shore of the Chesapeake Bay.

Numerous palisaded village sites have been excavated in the Ridge and Valley of southwestern Virginia (MacCord, 1999).

By the end of the Woodland era, much of the Middle Atlantic (i.e. inner Piedmont, Blue Ridge, Ridge and Valley, and eastern Appalachian Plateau) was apparently devoid of Indians except for the occasional transient group (Gardner, 1981). Historians and anthropologists believe the most likely scenario for the widespread depopulation of eastern North America was disease introduced by European explorers as early as 1539 when Hernando De Soto landed near Tampa Bay Florida (Walker & Miller, 1992; Whitney, 1994; Mann, 2005). Some anthropologists believe the origin of contagion was not De Soto's army, but the swine he brought with him as a food source (Mann, 2005).

Another theory for this phenomenon is that the increasing participation in the fur trade transformed the Indian way of life from a self-sufficient, bartering economy to a quasi-market condition, marked by increasing dependence on a foreign entity for their existence. This situation may have initiated political alliances that strained inter-Indian relationships (Walker & Miller, 1992). Activities during the French and Indian war (1750–1760) further reduced aboriginal populations and slowed rates of in-migration into the region (Gardner, 1981).

Early European Settlement

Human population numbers slowly rebounded with the influx of European settlers into the region in the mid 1700s. The early Euro-Americans relied on subsistence farming and free-range livestock grazing for their primary means of support (Whitney, 1994). Clearing land for agriculture was a slow and arduous process, often taking one or two generations to completely clear an entire tract of land (Whitney, 1994). Farmers used various means to prepare the land for planting. Trees were cut down or girdled, the roots dug up and hardwood stumps left to decay then dug out. The remaining slash or debris was burned and the ash tilled into the soil (Whitney, 1994).

As population increased and a market and cash economy became more important, hamlets and towns developed along expanding transportation networks (Gardner, 1981). By the early 1800s, much of the valley floor was used for agriculture, industry, or human habitation. The mountains increasingly became the focus of specialized activities such as lumbering, charcoal burning and mining (Gardner, 1981, Geier, 1981; Williams, 1998). Initially, only a small number of light industrial facilities and small-scale extractive industries (i.e. mills and iron works) were needed to provide products for local markets (Gardner, 1981; Whitney, 1994; Mann, 2005). Saw mills were usually the first manufacturing facility to be built in a new town. These were small-scale, low-capacity operations that typically produced less than 2000 board feet per day of timber (Whitney, 1994). Whitney (1994) notes more wood was used to provide fuel for domestic use (heating and cooking) than was used for building material.

Period of Extractive Industry

Virginia has a long history of iron manufacturing. Iron production involved transforming iron oxide into pig iron (alloy of iron and carbon). Cold blast furnaces supplied the high temperatures needed for the conversion, and charcoal provided fuel for the process. The production of charcoal was time-, labor- and resource-intensive, requiring 100–400 bushels of charcoal to produce one ton of pig iron (Whitney, 1994). Whisonant (1998) reports that each of the furnaces in Wythe County in southwest Virginia consumed on average 750 bushels of charcoal and 12 tons of iron ore to produce 5 tons of pig iron every 24 hours.

Historical records indicate that Jamestown colonists first mined iron ore in 1609. Archeologists unearthed the remains of a small charcoal iron furnace near Richmond that dates to 1619 (Whisonant, 1998). These were modest operations that produced agricultural tools, household implements and construction materials for local distribution (Gardner, 1981). The first large-scale production of pig iron took place near Fredericksburg in the early 1700s. Together, the Germanna and Massaponax furnaces produced 1200 tons of cast iron by the year 1732. The expansion of iron works began in earnest with the passage of the British Iron Act of 1750, which made the importation of pig iron into England duty free (Gordon, 1996). By the early 1800s, almost every county in Virginia, west of the Blue Ridge, had at least one charcoal furnace in blast. This trend continued into the mid-1800s with 45 furnaces and forges erected in the Ridge and Valley between 1826 and 1850 (Whisonant, 1998). Until the mid 1800s, the lack of overland transportation networks limited the construction of mills and iron works to streams and rivers, or within hauling distance of water transportation (Whitney, 1994). The rapid growth of urban areas increased the demand for lumber and the need for more cost-effective means of transport (Whitney, 1994). During the Civil War, Virginia iron was used to make weaponry for the Confederacy, but repeated assaults on ironworks in strategic locations drastically reduced production capacity. The 1870s and 1880s characterized the height of iron manufacturing in Virginia as charcoal furnaces were rebuilt and systematically converted to burn coke, thus reducing the demand on the forest for charcoal. These modifications increased productivity to over 90000 tons of ore per year. Despite the short boom in iron production most small furnaces could not compete with larger, more efficient operations in the Lake Superior region and were abandoned. The iron industry continued to decline despite newly discovered sources of iron ore in the early 1900s and by 1930s virtually disappeared from the Virginia landscape (Whisonant, 1998).

Improved band saw technology in the mid-1800s and especially the late-1800s made it possible to generate larger quantities of timber (Whitney, 1994; Brose *et al.*, 2001). Steam engines and the development of gear-driven locomotives facilitated the expansion of logging railroads into previously inaccessible areas, made it possible to move vast quantities of valuable timber throughout the eastern US (Whitney, 1994; Williams, 1998). Commercial logging between 1880 and 1930 was so intensive that in many areas forest cover was completely removed. Logging produced large quantities of woody debris or slash that was easily ignitable, especially during periods of drought. The combined effects of canopy removal and intense fires set the stage for massive, widespread erosion (Whitney, 1994; Williams, 1998; Brose *et al.*, 2001, Fowler & Konopik, 2007).

Era of Fire Suppression and Protection

Beginning in the 1920s, comprehensive conservation programs were implemented in an effort to reverse the damage caused by decades of destructive land use practices. Federal and state agencies purchased millions of acres of abandoned, degraded forest lands that had been cut or burned over. Today, large tracts of land are still owned and managed by the U.S. Forest Service, National Park Service and various conservation organizations (Whitney, 1994; Williams, 1998; Brose *et al.*, 2001).

Description and Location of Study Sites

The three study sites are located throughout the central Appalachian Mountains to facilitate regional-scale comparisons of spatial variability in fire regimes and vegetation dynamics (Fig. 3.1). Suitable sites for sampling were identified on the basis of (1) multiple neighboring pine stands with intervening oak forests, (2) sufficient evidence of past fire (40 pine trees or snags samples exhibiting multiple fire scars), (3) minimal anthropogenic disturbance that might obscure the fire record and (4) ease of accessibility. Because the pine stands are interspersed among the oak stands, I was able to use the fire history recorded by the fire-scarred pines to characterize the fire regimes of the surrounding oak forests as well.

Mill Mountain

The study site is on the northwest side of Mill Mountain (37°53′ N, 79°38′ W) in Bath County, Virginia (Fig. 3.2) with elevations ranging from 690–900 m. Small streams dissect the mountainside, with alternating drainages and spurs aligned southeast to northwest. Mill Mountain is in the Ridge and Valley physiographic province. Annual precipitation averages 1090 mm at Hot Springs, Virginia, 20 km to the northwest at 680 m elevation (National Climatic Data Center, 2002). Mean monthly temperatures are

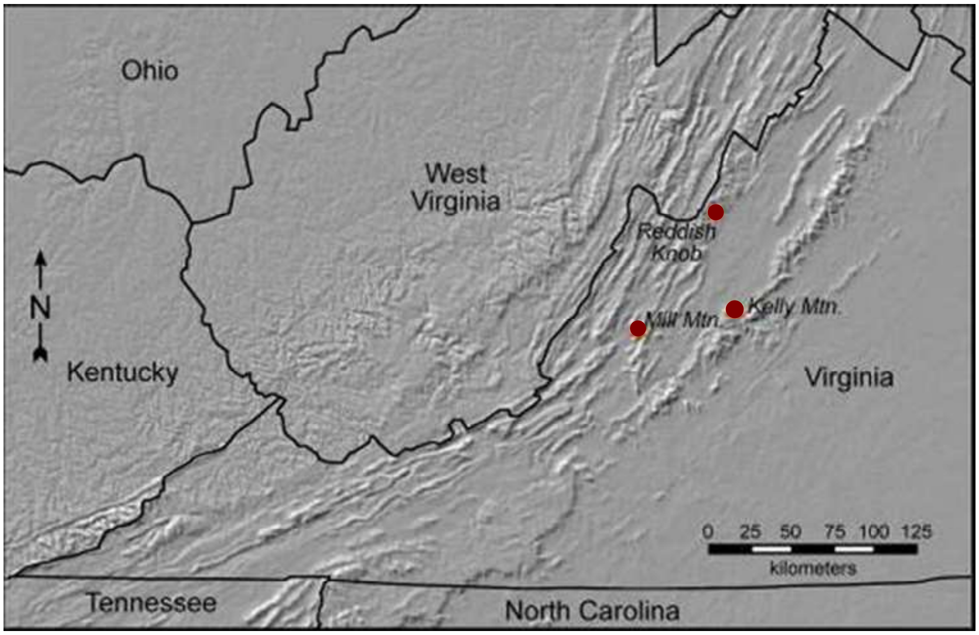

Figure 3.1 Location of study sites, Virginia, USA.

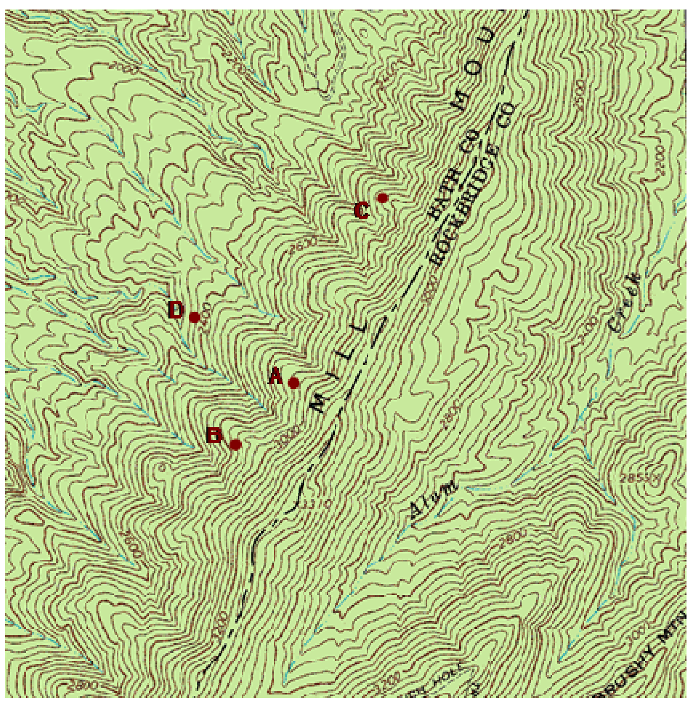

Figure 3.2 Mill Mountain study site showing the locations of stands A–D. Stand C was sampled for fire history only. Oak stands were not sampled at Mill Mountain.

between -1°C and 22°C. The vegetation cover is representative of central Appalachian landscapes, with the typical oak-dominated forest matrix covering most of the landscape, the mesophytic tree species confined to valleys and lower slopes, and the xerophytic pine–oak stands situated on narrow ridgetops and west-facing slopes. These xerophytic stands are dominated by yellow pines, particularly the Appalachian endemic Table Mountain pine, along with pitch pine, chestnut oak, and northern red oak (Williams, 1998). These trees are relatively shade-intolerant and have adaptations to fire such as thick bark and, in Table Mountain pine, serotinous cones. A dense hardwood understory is dominated by black gum, red maple and mountain laurel (*Kalmia latifolia*).

Native Americans lived along the Cowpasture River and other rivers in Bath County, but the area was apparently a hinterland without large permanent populations or well-developed agriculture (Geier & Boyer, 1982). The sites were abandoned by the 1600s, concurrent with depopulation throughout western Virginia a century or more in advance of European settlement (Egloff & Woodward, 2006), but hunting, trading and raiding parties continued to travel through western Virginia in the 1700s. European settlement began along the Cowpasture River southwest of the study site *c*. 1745 (Morton, 1917). Mill Mountain is within a rugged area occupied by few humans in the past (Morton, 1917) or today. Land records (GWNF headquarters) indicate that original land grants on Mill Mountain were made *c.* 1795–1825. Scattered settlement may have occurred during that period. Of potential importance for fire history is that iron furnaces operated near Longdale, 9 km from the study site, from 1827 to 1925, consuming hardwood timber to produce charcoal until conversion to coke in 1874 (Russ *et al.*, 1995). By the 1870s–1880s, furnaces and associated settlements extended along Simpson Creek to within about 4 km of the study site, but the settlements were abandoned after iron production ceased (Russ *et al.*, 1995). A railroad was constructed along Pads Creek in 1857 (Morton, 1917) and continues operation. Logging occurred along South Fork Pads Creek in 1927–1928. In 1937, the United States Forest Service (USFS) purchased a 10526 ha area containing Mill Mountain. The land records mention repeated burning in the past and describe a specific fire that burned much of Mill Mountain in 1930. Fire records for 1970 to present contain no wildfires for the study site since 1970 (USDA Forest Service, 1998). A prescribed fire conducted on 27 March 2001 affected part of the study area (stand D, Steve Smestad, GWNF, personal communication). It was a mild burn that consumed fine fuels and top-killed some understory plants, but appeared to have little influence on larger saplings or overstory trees.

Kelley Mountain

The Kelley Mountain study area is located in Augusta County, Virginia (37º55′N, 79º2′W), and is within the Blue Ridge province (Fig. 3.3). Kelley Mountain has relatively flat ridge tops with steeply sloping ridges and hollows (Tolley, 1983). Elevations range from 930–1010 m. Annual precipitation averages 938 mm at Staunton, Virginia, 24 km to the north at 450 m elevation (National Climatic Data Center, 2002). Mean monthly temperatures are between 1°C and 22°C.

The pine stands contain a mixture of yellow pines and hardwoods, mainly Table Mountain pine, pitch pine, chestnut oak, and black gum; however white pine is present

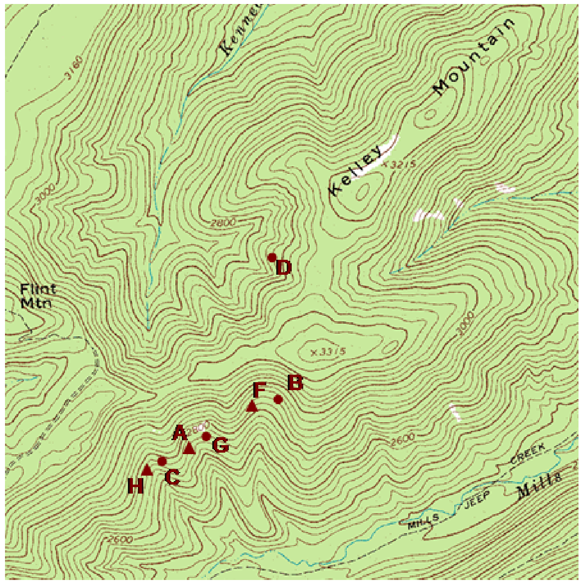

Figure 3.3 Kelley Mountain study site showing the location of stands A–H. Locations of pine stands are indicated by ● and locations of oak stands are denoted by ▲ . Stand D was sampled for fire history only.

as well. The intervening hardwood stands contain primarily chestnut oak and black gum. Black gum, pignut hickory (*Carya glabra*) and striped maple (*Acer pensylvanicum*) comprise the understory vegetation and mountain laurel dominates the dense shrub layer. There is abundant evidence of aboriginal occupation in the area during the Early- Late Archaic and Woodland periods (8000–2800 BP; 2800–1300 BP). Cultural surveys conducted during 1979 and 1980 revealed activity along Mill Creek (1 km southeast of the study site) and along the base of an expansive alluvial fan that extends to the South River (5 km north of study site). A number of base camps, limited activity camps, quarry sites and reduction stations have been identified in the upland regions of nearby Kennedy Ridge, northwest of Kelley Mountain. These sites are located on relatively flat areas near spring heads or upland swamps and bogs. It is possible the camps were only seasonally occupied (late summer through fall) to take advantage of maturing nuts and berries and to replenish lithic resources (Tolley, 1983).

Euro-American settlement began in the area that is now Augusta County in the early 1730s, and the county itself was officially recognized in 1745. Staunton, the county seat, was founded in 1761 (Peyton, 1953). Peyton (1953) reports a “Great influx of population into the valley” in the early 1730s. By the late 1700s, the population of Augusta County was over 10000 (Peyton, 1953). Although the population of Augusta County grew rapidly throughout the century, it appears settlement near the study area remained sparse as the first original land grants were not issued until 1796 and 1797, decades after the main valley was settled (GWNF land records).

Both manganese and iron have been mined extensively in Augusta County. The facility with the most potential to impact the study site was the Mt. Torry Furnace (6.4 km to the north). The furnace was built in 1800 and operated until it was destroyed in 1864 during the Civil War. It was rebuilt shortly thereafter and continued in operation until 1885. Other mines or furnaces that may have impacted the site are located near Stuarts’s Draft and Waynesboro in Augusta County and the Lyndhurst-Vesuvius mining district, in Rockbridge County, near the border of Augusta County (Watson *et al.*, 1907).

The study site is located on three different tracts purchased by the USFS. KMA and KMH are located within a tract acquired by the USFS from the city of Staunton in 1923 and 1924. Just prior to acquisition, land records (GWNF headquarters) report that chestnut and oak was present on the upper slopes. The ridges contained chestnut oak, northern red oak and Virginia pine (*Pinus Virginiana*) with a dense growth of shrub oak

(*Quercus* spp.) in the understory. Most of the merchantable timber had been removed by repeated cutting and frequent, severe fire, but excellent timber remained in the hollows. KMB and KME are part of 329 ha tract acquired by the USFS in 1924. Originally, the upper slopes supported stands of mixed oaks, chestnut and yellow pine. Ridges contained low-grade chestnut oak, northern red oak and pitch pine. Scrub oak and mountain laurel were present in the understory. The entire tract was heavily affected by multiple disturbances, i.e. logging, fire and ice.

The tract containing KMF and KMG was acquired in 1923 and 1924. This tract apparently never was logged, but had been subjected to repeated, severe fires that reduced the young growth to a stunted condition. Scrub oak was the predominant species on the ridges and upper slopes. All yellow pine in the vicinity reportedly were killed during a southern pine beetle (*Dendroctonus frontalis* Zimmermann) outbreak that occurred *c.* 1886, however, small pines likely survived because numerous studies indicate that only the large pines are vulnerable to attacks by southern pine beetle.

Reddish Knob

The study site is located just above the Briery Branch Dam in southwestern Rockingham County, Virginia (38º26′N, 79º9′W), and is in the Ridge and Valley physiographic province (Fig. 3.4). Annual precipitation averages 903 mm at Dale Enterprise, Augusta County, Virginia, 22 km to the northeast at 427 m elevation (National Climatic Data Center, 2002). Mean monthly temperatures range from 1°C to 22°C. Yellow pine forests occupy southwest-facing slopes of spurs along the north side of Wolf Ridge, while the intervening oak forests inhabit the alternating, southeast-facing slopes. Elevations of these sites range from 630–900 m. The pine stands are comprised of Table Mountain pine and pitch pine in the overstory, with black gum and red maple in the understory. The shrub layer is thick with mountain laurel and mountain fetterbush (*Pieris floribunda* (Pursh) Benth. & Hook. F.). Chestnut oak is the dominant overstory species in the oak stands, along with a small component of northern red oak and red oak. Black gum, red maple and pignut hickory make up a large portion of the understory species.

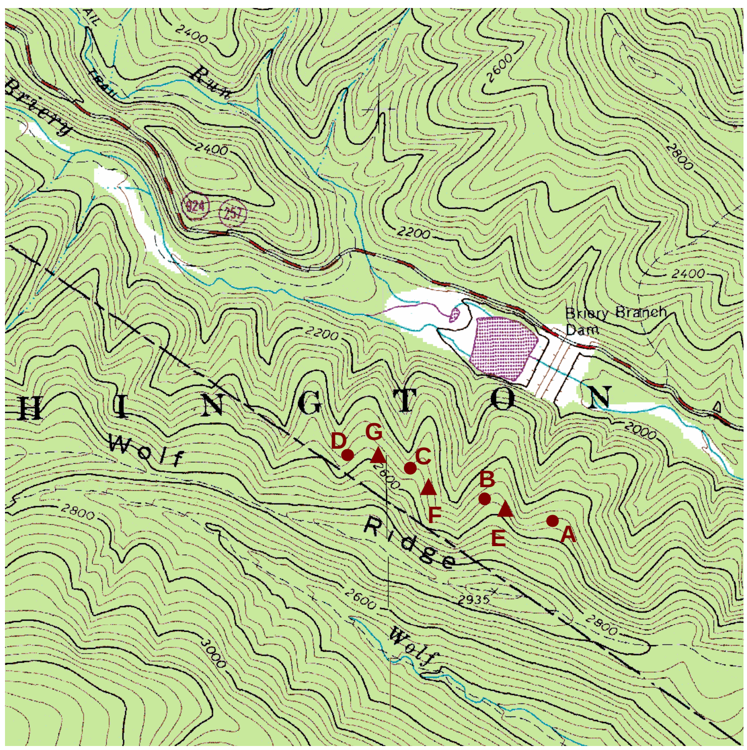

Figure 3.4 Reddish Knob study site showing the location of stands A–G. Locations of pine stands are indicated by ● and locations of oak stands are denoted by ▲ . Stand D was sampled for fire history only.

There is little indication of aboriginal occupation in the vicinity of the study site, with the exception of a prehistoric camp along Wolf Run Creek, approximately 3 km from the study site (Nash, 1991). Euro-American settlement began in the region in the 1720s. Most early settlement occurred in the eastern portions of what is now Rockingham County. The earliest land grants (*c.* 1750) were issued for lands situated along the Shenandoah River near the present day towns of Port Republic and The Grottoes. Rockingham County was formed in 1777 (Wayland, 1912).

The study site is located in a remote region of the county that was apparently never heavily populated (Sherwood, 2010). The issuance of land grants in the vicinity began in 1772, although settlement along Briery Branch did not occur until around 1796 (GWNF Headquarters). Original land grants on Wolf Ridge were issued in 1832 and 1847. The Forest Service acquired the tracts in 1916. Land records (GWNF Headquarters) indicate no agriculture in the vicinity, but cattle grazing was extensive in the area and there may have been some logging in the Little River and Briery Branch basins. Iron and coal was mined at a number of areas in the county (McCreath, 1884; Wayland, 1912); however, none of these sites were in close enough proximity to the study site to have had an effect on the fire regime.

Vegetation at the time of USFS acquisition is described as good timber containing a variety of hardwood species and both white and yellow pine. Frequent fire had rendered ridge tops and western exposures bare of timber, leaving only a ground cover of pitch pine and scrub oak. The area was affected by southern pine beetles in the late 1880s.

Field Methods

Aerial photographs taken prior to leaf out of deciduous trees, combined with information from USFS personnel, were used to identify potential sample sites. These sites were then intensively surveyed for the presence of living pine trees or remnant pine wood (i.e. stumps, snags or logs) containing multiple fire scars. During 2003–2006 field seasons, full or partial cross-sections were cut from living and dead Table Mountain pine and pitch pine trees with basal fire scars in four adjacent pine stands at each study site (Arno & Sneck, 1977).

To characterize age structure and tree species composition, we established one 50 m × 20 m plot in three of the four pine stands and one 50 m × 20 m plot in each of the three intervening oak stands at each site. Two cores were extracted from opposite sides at the base of each living tree with stem diameter at breast height (DBH, measured at 1.37 m) ≥ 5 cm, and the species and DBH were recorded. Saplings (height ≥ 50 cm, DBH < 5 cm) were identified and counted, but not cored. However, branch nodes were counted to estimate the age of pine saplings (Pfeffer, 2005). Seedlings (height < 50 cm) of all tree species in a 10 m × 20 m subplot in each quadrat were inventoried. Twenty cross-sections were cut from the largest mountain laurel shrubs in each stand to estimate when shrub establishment began.

Laboratory Methods

Prior to surfacing, increment cores were mounted on wooden core mounts with the tracheids aligned vertically (Stokes & Smiley, 1968). Some of the larger fire-scarred samples were re-sectioned with a band saw to search for hidden fire scars. Fragile cross-sections were mounted on plywood to provide stabilization when sanded. Increment cores, pine cross-sections and mountain laurel cross-sections were surfaced with a belt sander using progressively finer abrasive belts (ANSI 40-grit [500–595 µm] to 400-grit [20.6–23.6 µm] until the cellular structure of the wood was easily visible under standard magnification (Orvis & Grissino-Mayer, 2002).

The tree rings of all increment cores and cross-sections were crossdated visually and assigned a calendar year using established techniques of comparing patterns of narrow and wide annual rings between samples (Stokes & Smiley, 1968; Fritts, 1976). Crossdating is possible because trees over a wide geographic area often respond similarly to broad-scale climatic and environmental variability (Stokes & Smiley, 1968; Fritts, 1976). These patterns are also observable in remnant trees and wood fragments, thus crossdating can be used to accurately assign calendar dates to non-living trees (Fritts, 1976). The tree-rings were then measured to the nearest 0.001mm using a Velmex measuring system and J2X measurement software.

The tree-ring measurements were entered into the software program COFECHA to verify the crossdating and measurement accuracy (Holmes, 1983; Grissino-Mayer, 2001a). COFECHA can also be used to aid in dating samples that are difficult to crossdate visually. Correlation analysis was performed on each tree-ring series using overlapping 40-year segments lagged by 20 years. Segments falling below the critical correlation coefficient of 0.37, representing the 99% confidence level, were flagged for reinspection and I made dating or measurement corrections as required.

A master tree-ring chronology was developed from pine cores and cross-sections with the longest tree-ring record to aid in dating samples with no pith or bark date (Dieterich & Swetnam, 1984). For cores and cross-sections that did not intersect the pith, tree age was estimated from the width and curvature of the innermost rings (Applequist, 1958).

After the cross-sections were assigned calendar years, the fire scars were dated to the year of scar formation. Fire seasonality was estimated by noting the position of the fire scar within the annual ring (Baisan & Swetnam 1990). Seasonal designations include (1) dormant, occurring between the latewood of one ring and the earlywood of the next; (2) earlywood, occurring within the first third of the earlywood; (3) latewood, occurring in the latewood band and (4) undetermined, seasonality of scar cannot be determined. Fire history information (fire dates, seasonality, inner/pith and outer/bark dates) were then entered into the fire-history analysis software FHX2 for graphing and statistical analysis (Grissino-Mayer, 2001b).

To obtain an estimate of age for the mountain laurel samples, the rings were counted, but not crossdated. Mountain laurel is difficult to crossdate because ring boundaries are not always expressed clearly and it is often not possible to identify the boundary between the outermost ring and the bark.

Data Analysis

Fire History

I used the Weibull Median Interval (WMI) and the widely used Mean Fire Interval (MFI) to characterize central tendency in the fire return intervals. Lower and Upper Exceedance Intervals (LEI and UEI) were calculated to characterize the range of historical variability within the Weibull-modeled distribution. Specifically, 75% of the fire intervals are expected to fall between the LEI and UEI. In consideration of uncertainties inherent in fire-scar analyses (Baker & Ehle, 2001; van Horne & Fule´, 2006) five different estimates of WMI, MFI, LEI and UEI were obtained, each of which has advantages and disadvantages. (1) The point fire interval was calculated from the fire intervals recorded by individual samples and is an estimate of fire frequency at any point on the landscape. In its calculation, FHX2 analyses only the intervals covered by ‘‘recorder’’ years (i.e. years following the initial scar on a tree) (Grissino-Mayer, 2001b). The initial wound makes the tree more susceptible to subsequent scarring. Also, tree rings formed after a tree has healed completely over a wound, or during a period in which some of the scars may be obscured by decay or removal by subsequent fires, are not considered recorder rings (Grissino-Mayer, 2001b). The designation of recorder years is a standard and necessary practice (Grissino-Mayer *et al.*, 2004) to ensure that MFI and other calculations are based on periods when data are available. Limiting the analysis to intervals covered by recorder years prevents the bias that could result from including intervals that appear to have been fire-free for a long time simply because the scars were removed or the tree was not susceptible to scarring. Nonetheless, the point fire interval likely overestimates fire interval length because trees are imperfect recorders of all the fires that burn them even if they are functioning as recorders. (2) The stand-level composite fire interval was calculated using all fires recorded by all trees in a stand. Generally, non-recording intervals of one tree are covered by recording intervals of other trees; therefore FHX2 uses all the composite fire intervals to estimate fire frequency (i.e. no fire scar on any tree is excluded from analysis). Compositing the fire records from multiple trees reduces the likelihood of missing a fire. However, some fires might be missed because of the limited number of fire-scarred trees in each stand, causing the fire interval to be overestimated. (3) The combined stand composite fire interval was based on all fires recorded by all trees in all stands. This is a standard analysis conducted to minimize the likelihood of missing a fire, but it could underestimate fire interval if some of the fires did not burn the entire study area. It provided the most complete record of fire activity in the study area and was useful for investigating temporal trends in burning. (4) The filtered composite fire interval for all stands combined was based only on ‘‘major’’ fires recorded by at least two trees and ≥ 25% of all recorder trees; such fires may have been more extensive or severe than others. By disregarding potentially small-extent fires, filtering offers a more conservative and possibly more reliable estimate of fire frequency. (5) The area-wide fire interval (Fisher *et al.*, 1987) was based solely on widespread fires recorded in all four stands, if the year of the fire was a recorder year in all stands. For fire years that were recorder years in only two or three stands, an area-wide fire was one that scarred trees in all of those stands. I did not consider fires that occurred when only one stand had recorder years.

Temporal Variations in Fire Intervals

To investigate temporal trends in burning, I calculated the mean number of fire scars per recording tree per decade (sensu Hoss *et al.*, 2008). This method permits a comparison across decades with different sample sizes of recording trees. I used correlation analysis (Zar, 1999) to determine if the mean number of scars per recording tree changed over time.

Fire-climate Relationships

I used Superposed Epoch Analysis (SEA), which is available in FHX2, to investigate relationships between interannual variations in fire activity and climatic variability (Baisan & Swetnam, 1990; Swetnam, 1993; Grissino-Mayer & Swetnam, 2000; Grissino-Mayer, 2001b). SEA evaluates climatic conditions (e.g. precipitation or temperature) prior to and during fire years by first stacking the fire event years, setting them to year zero, then calculating the average climate conditions prior to, and during individual fire years (Grissino-Mayer, 2001b; Grissino-Mayer, 1995). SEA uses Monte Carlo techniques to establish confidence intervals of observed departures from the mean (Veblen, 2003). Fire occurrence was compared with proxy climate indices reconstructed from tree rings to see if precipitation was significantly different from average before (t - 6), and during (t = 0) the fire event. For the proxy climate indices, I used a tree-ring reconstruction of summer (June-August) Palmer Drought Severity Index (PDSI), Grid 247, from western Virginia available for download from the National Climatic Data Center (NCDC, 2002). Grid 247 is part of a gridded network of PDSI reconstructions covering most of North America. The network was generated from 835 tree-ring chronologies, some extending back 2000 years. Each of the 286 grid points cover 2.5° × 2.5° (Cook *et al.*, 2004). The temporal coverage of Grid 247 is 1612 years (367–1979) and contains up to 30 tree-ring chronologies; however only nine chronologies were used in the reconstruction from 1638–1930 (Cook *et al.*, 2004).

PDSI, developed by Palmer (1965), is widely used to examine spatial and temporal characteristics of drought as well as the severity of drought across the United States (Alley, 1984; Cook *et al.*, 2004). PDSI values are calculated from instrumental measurements of precipitation, temperature, and available soil moisture (Alley, 1984). Values range from -6 to +6, with negative values indicating dry conditions and positive values indicating wet conditions. Values greater than or less than four indicate extreme climatic conditions (Meldahl *et al*., 1999). A disadvantage of using the PDSI to investigate fire–climate relationships is the temporal limitation imposed by the use of instrumental records to derive PDSI values. However, tree-ring reconstructions of past climates are widely used to augment the instrumental record and extend the evaluation of drought variability (Woodhouse & Overpeck, 1998; Quiring, 2004; Cook *et al.*, 2007).

I conducted SEA on three different fire event data sets per site: (1) all fires (AF) recorded by all trees at each study site; (2) major fires (MF) recorded by at least two trees and ≥ 25% of all recorder trees and (3) area-wide (AW) analysis including fires that occurred on at least two of the three study sites. I also performed analysis on subsets of the above data based on seasonality of the fires: dormant-season fire years (DS); growing-season fire years (GS); and years with fires recorded with any season (AS).

I used simple linear correlation to examine the relationship between fire activity and mean reconstructed decadal PDSI for each study area. Additionally, I calculated region-level fire activity by averaging mean number of fire scars per recording tree per decade across all three study areas then used simple linear correlation to examine the relationship between fire activity and mean reconstructed decadal PDSI.

Vegetation Dynamics

Tree age and DBH were graphed to portray stand age and size structure. For cores that did not intersect the pith, tree age was estimated from the width and curvature of the innermost rings (Applequist, 1958). Because the age structure histograms were created using 10-year age classes, trees with >10 years added were excluded.

Also, ‘‘moderate releases’’ and ‘‘major releases’’ (Lorimer & Frelich, 1989) were identified in the ring-width measurements from all the pine and hardwood cores to detect growth increases that could signal major fires or other canopy-thinning disturbances that may have promoted tree establishment. A moderate release was an abrupt ring-width increase (≥ 50% increase in a year, relative to the mean for the previous 10 years) that was sustained for a decade (i.e. the mean ring width for the decade following the increase was > 50% more than that of the previous decade). A major release had a threshold of 100% increase in ring width relative to the previous decade.

Stem density and basal area were calculated to determine the current species composition of the pine and oak stands. Finally, ages of mountain laurel stems were graphed to portray establishment dates. Since I was only interested in estimating the beginning of shrub establishment relative to fire history, I did not attempt to characterize the age structure of the shrub population, thus the graphs portray only the establishment dates of the largest, and presumably oldest shrubs.

CHAPTER IV

RESULTS*

Fire History

The fire history reconstructions for this study were based on 231 fire-scars collected from the three study sites. I was able to assign fire dates to 1114 scars, which revealed 164 fire dates. The length of the fire chronologies varied between sites and ranged from 318 to 416 years (Table 4.1).

Table 4.1 Summary of fire history data by site.

Site	Length of Chronology	Number of Specimens	Number of Scars	Number of Fire Dates	Inner Ring	Outer Ring	First Fire Scar	Last Fire Scar
Mill Mountain	318	63	201	43	1637	2003	1704	1930
Kelley Mountain	416	92	495	62	1598	2005	1638	1921
Reddish Knob	356	76	418	55	1670	2005	1671	1913
Total		231	1114	164				

Fire history charts for each site illustrate a regime of frequent fires (Figs. 4.1–4.6) including many widespread fires that affected all of the stands at each site (Fig. 4.7). For scarred trees that could be aged (i.e., had an intact pith), mean age at initial

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scarring was 16.6 years (range 4–70 years) at the height of the cross-section. Mean diameter (excluding bark) at initial scarring was 5.9 cm (range 0.6–21.5 cm) (Table 4.2).

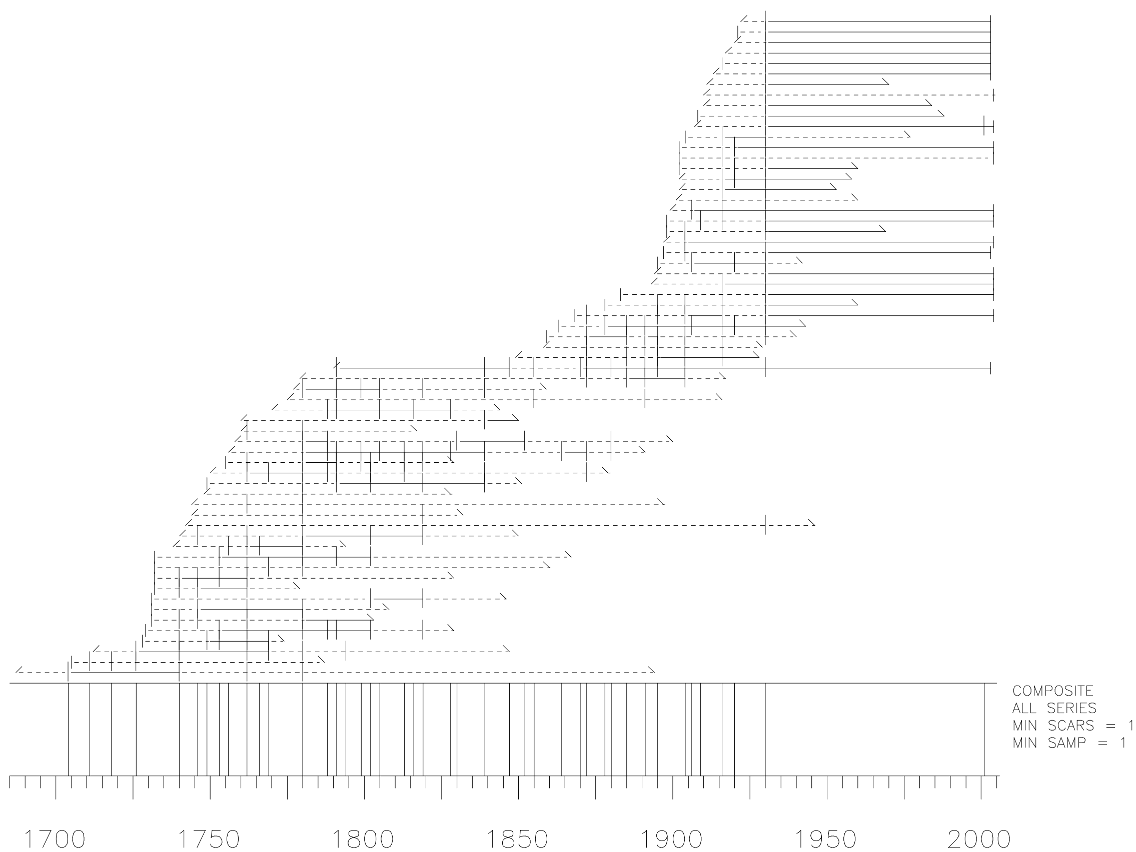

Figure 4.1 Unfiltered fire chronology for Mill Mountain showing the record of fire scars for each tree, 1704–2003. Horizontal lines indicate the time spanned by each tree, and short vertical bars represent dated fire scars.

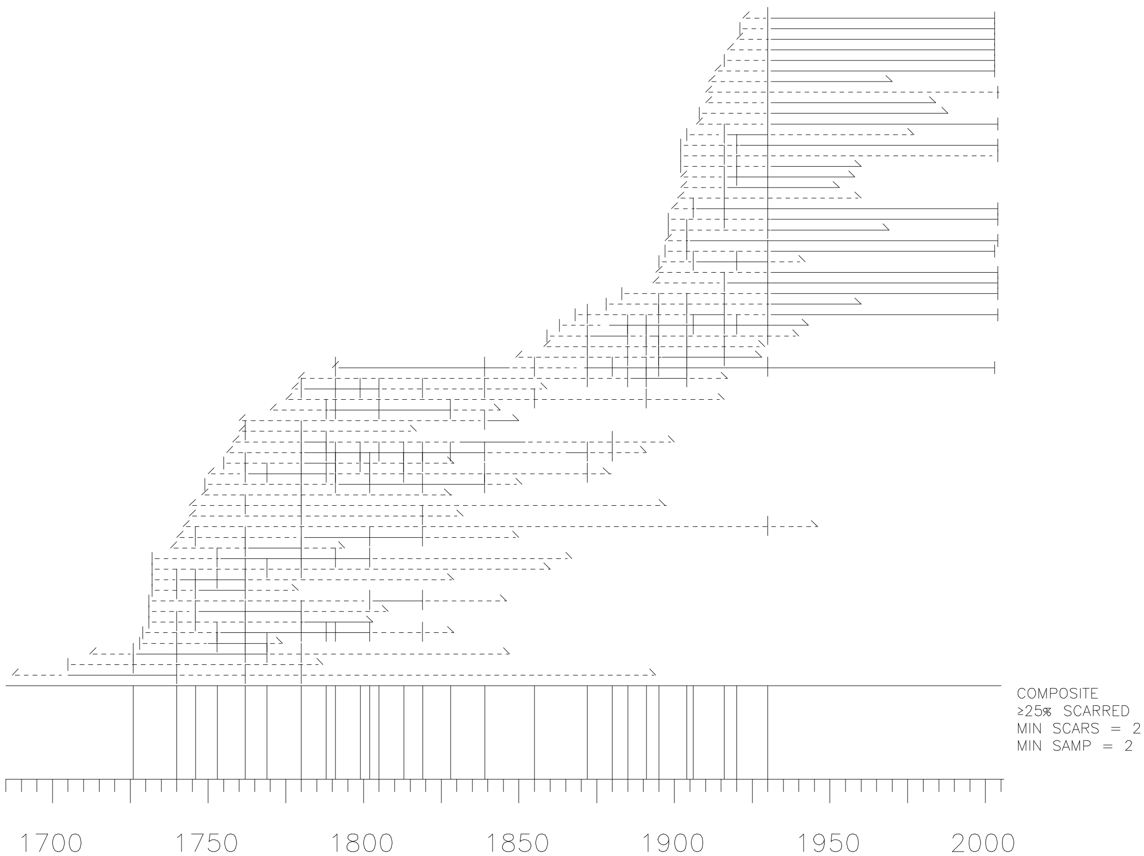

Figure 4.2 Filtered fire chronology for Mill Mountain. The filtered composite fire interval for all stands combined based only on “major” fires recorded by at least two trees and ≥ 25% of all recorder trees. Horizontal lines indicate the time spanned by each tree, and short vertical bars represent dated fire scars.

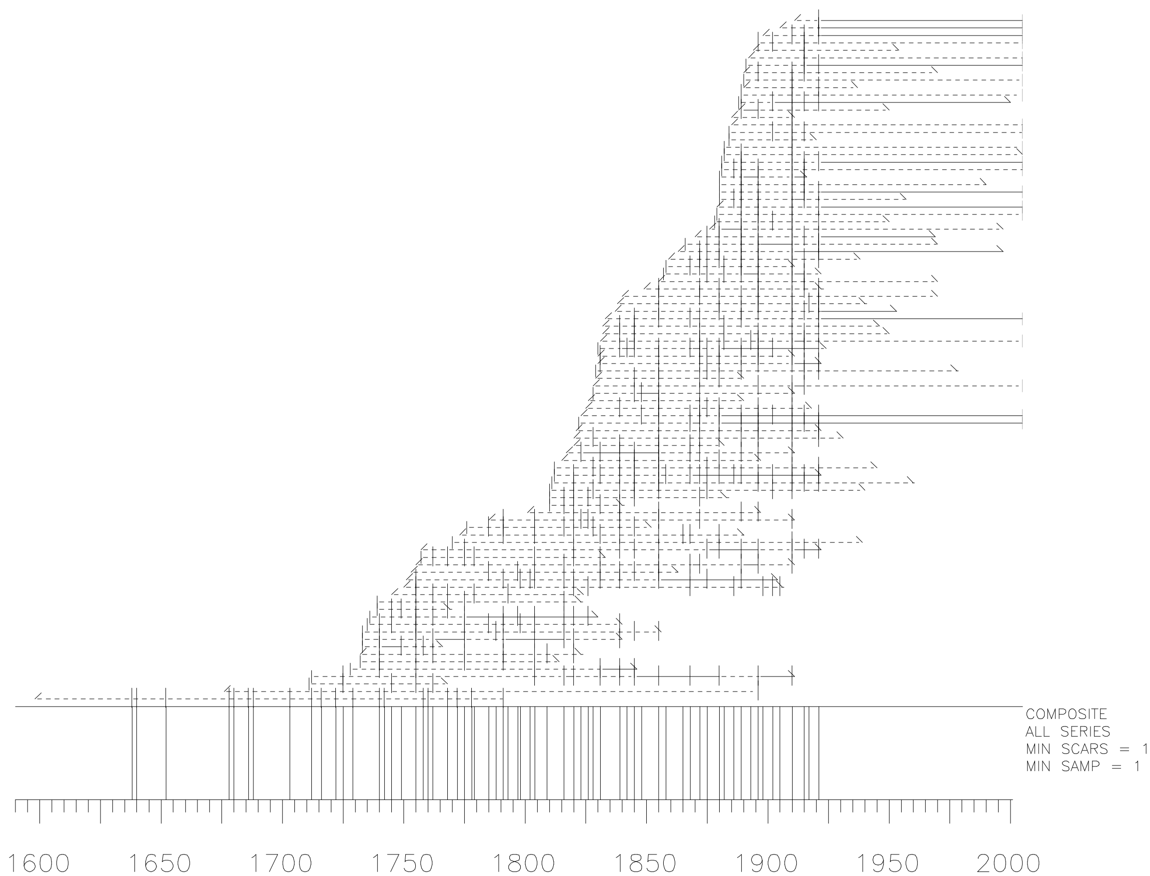

Figure 4.3 Unfiltered fire chronology for Kelley Mountain showing the record of fire scars for each tree, 1598–2005. Horizontal lines indicate the time spanned by each tree, and short vertical bars represent dated fire scars.

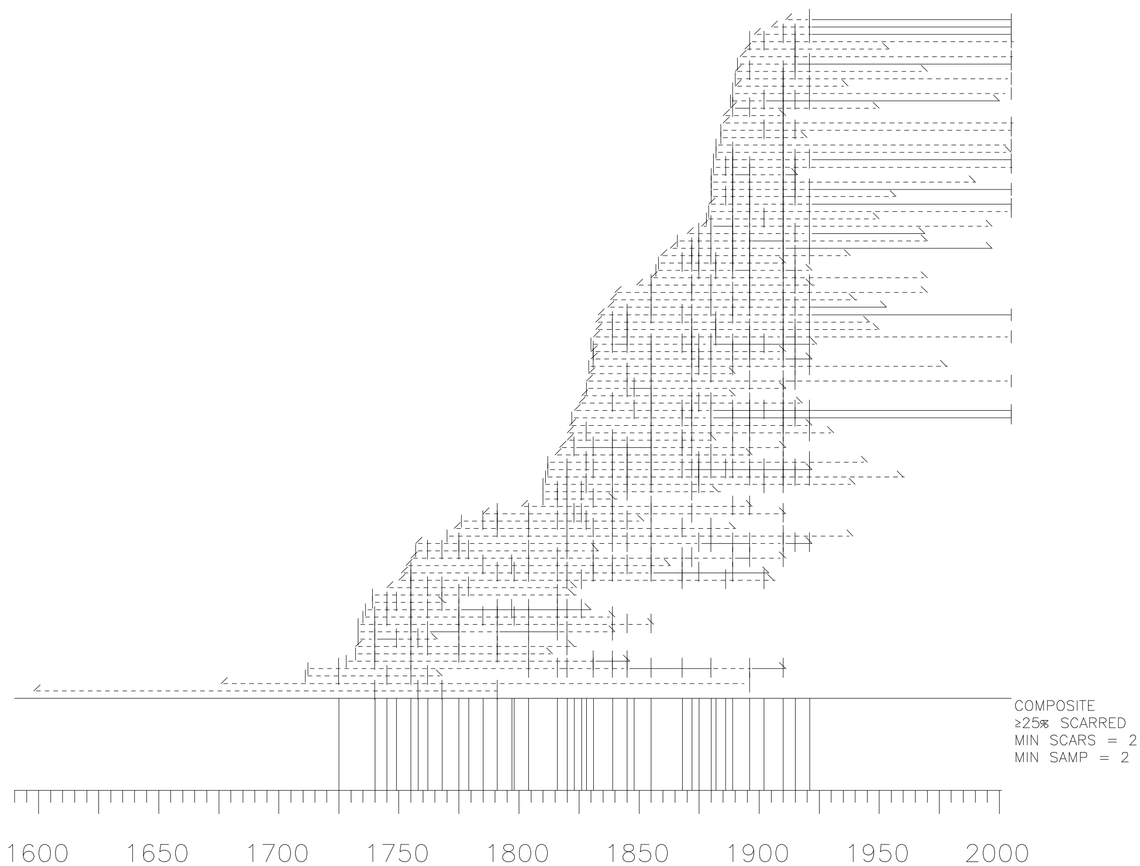

Figure 4.4 Filtered fire chronology for Kelley Mountain. The filtered composite fire interval for all stands combined based only on “major” fires recorded by at least two trees and ≥ 25% of all recorder trees. Horizontal lines indicate the time spanned by each tree, and short vertical bars represent dated fire scars.

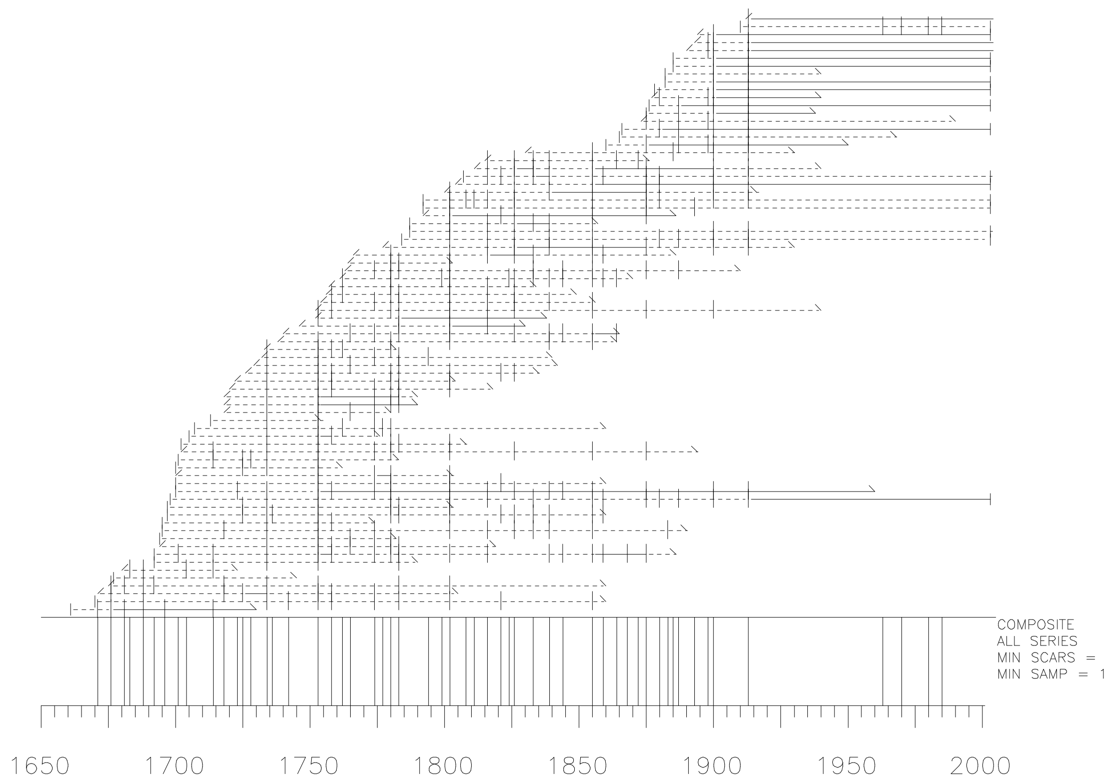

Figure 4.5 Unfiltered fire chronology for Reddish Knob showing the record of fire scars for each tree, 1670–2005. Horizontal lines indicate the time spanned by each tree, and short vertical bars represent dated fire scars.

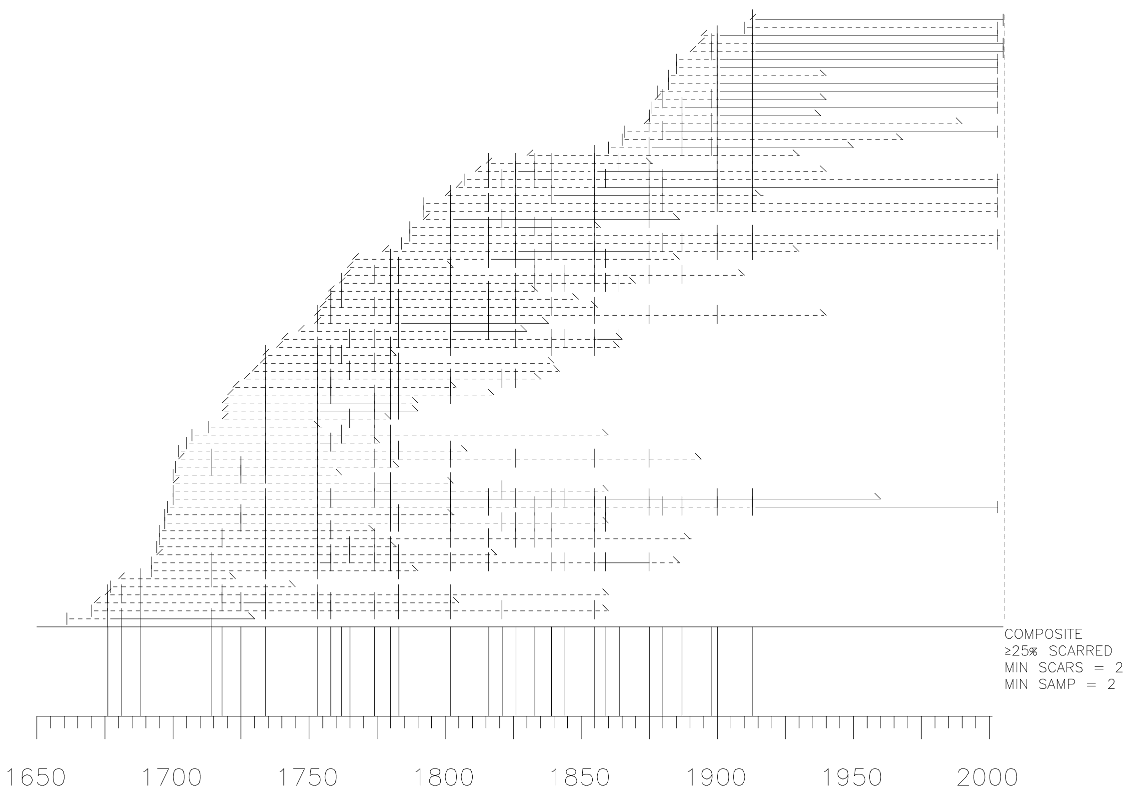

Figure 4.6 Filtered fire chronology for Reddish Knob. The filtered composite fire interval for all stands combined based only on "major" fires recorded by at least two trees and ≥ 25% of all recorder trees. Horizontal lines indicate the time spanned by each tree, and short vertical bars represent dated fire scars.

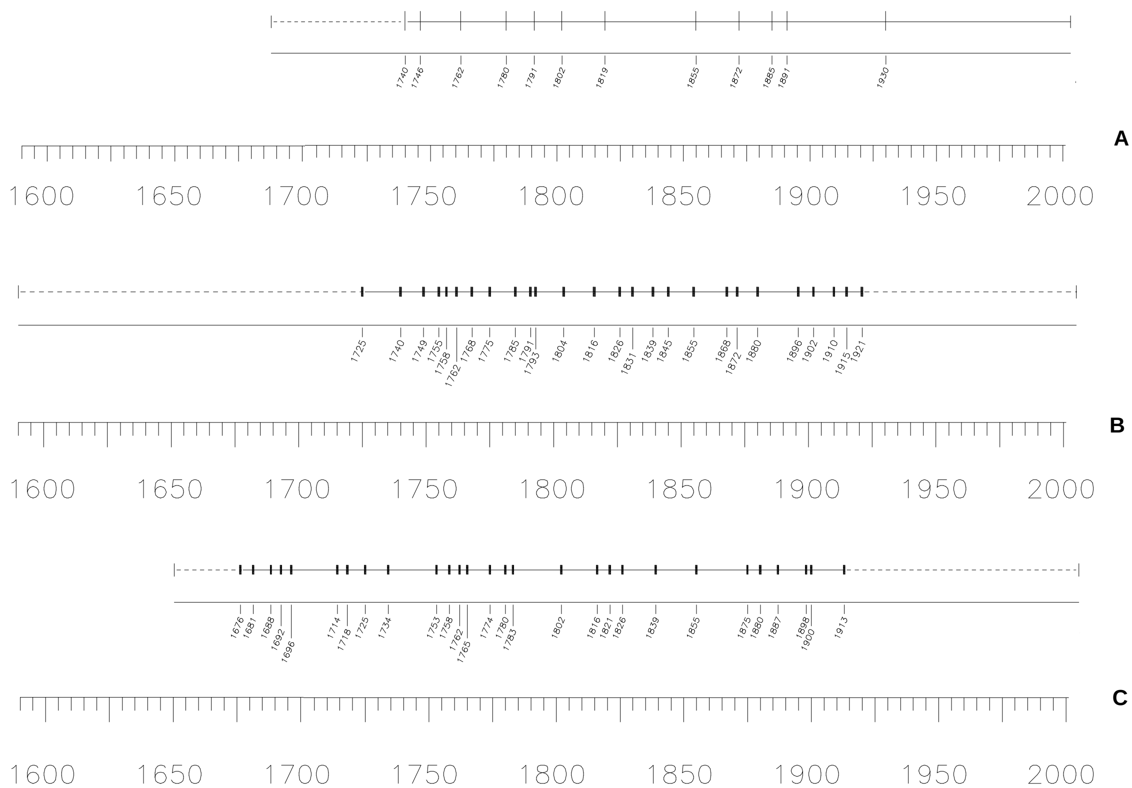

Figure 4.7 The area-wide fire interval for (A) Mill Mountain; (B) Kelley Mountain; and (C) Reddish Knob based on widespread fires recorded in all four stands, if the year of the fire was a recorded year in all stands. For fire years that were recorder years in only two or three stands, an area-wide fire was one that scarred trees in all of those stands.

Table 4.2 Mean age and diameter of cross-sections at initial scarring.

Site	Mean Age (years)	Mean Diameter (cm)
Mill Mountain	19.7 (Range 7–70); n = 38	6.1 (Range 0.6–12.1); n = 37
Kelley Mountain	12.6 (Range 5–33); n = 40	5.1 (Range 1.6–10.8); n = 33
Reddish Knob	12.8 (Range 4–33); n = 37	5.6 (Range 1.6–10.8); n = 31
All Sites	16.6 (Range 4–70); n = 115	5.9 (Range 0.6–12.1); n = 101

Fires occurred regularly from the beginning of each fire chronology until the early 1900s (Fig. 4.8); correlation analysis indicated that the number of fires per decade did not change during this time (Mill Mountain $r = 0.205$, $P = 0.336$, $df = 22$; Kelley Mountain $r = 0.033$, $P = 0.865$, $df = 27$; Reddish Knob $r = 0.073$, $P = 0.718$, $df = 23$). One post-1930 scar was observed on Mill Mountain: a dormant-season scar caused by a prescribed burn of 2001. One specimen from Reddish Knob recorded four post-1930 fire-scars: one in 1963 of undetermined seasonality; one dormant season scar in 1970; and two early season scars in 1980 and 1985. Because I am interested in the pre-suppression fire-regime, I excluded fire-intervals from the correlation and fire interval analyses that followed the last major fire event at each site. For the period beginning in the first year with two or more scarred trees (Grissino-Mayer *et al.*, 2004) and ending with the last major fire event, the various analyses yielded MFI and WMI estimates of 3.7–17.4 years (Tables 4.3A–C).

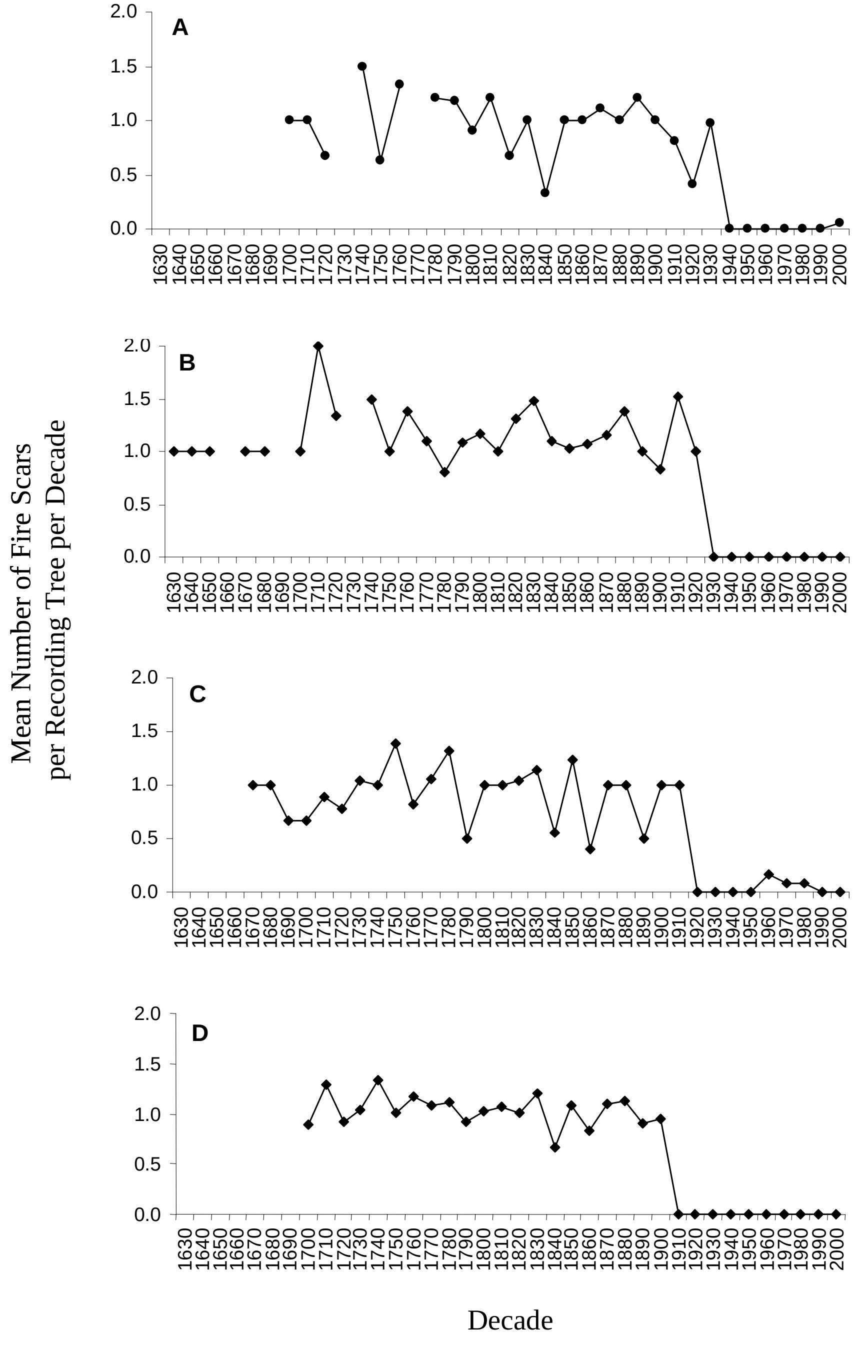

Figure 4.8 Decadal fire activity for (A) Mill Mountain; (B) Kelley Mountain; (C) Reddish Knob: and (D) Region-level. Gaps in the data are decades with no recorder trees available for calculation.

Table 4.3A. Fire interval calculations for Mill Mountain. Abbreviations: MFI = mean fire interval; WMI = Weibull median interval; SD = standard deviation; LEI = lower exceedance level; UEI = upper exceedance level.

Mill Mountain	MFI	WMI	SD	LEI	UEI	Range	Number of intervals	Years covered
Point fire interval (n=63)	11.1	10.2	6.7	4.1	18.8	2–48	82	1726–1930
Stand-level composite fire interval								
Stand A (n=17)	7.3	6.6	5.0	2.4	12.9	2–26	26	1740–1930
Stand B (n=19)	11.9	10.0	9.7	3.0	22.0	3–39	16	1740–1930
Stand C (n=14)	15.9	11.7	19.4	2.5	32.4	4–59	7	1819–1930
Stand D (n=13)	8.3	8.1	3.9	4.2	12.6	4–16	7	1872–1930
Combined-stand composite fire interval	5.4	5.1	2.9	2.2	8.8	2–14	38	1726–1930
Filtered composite fire interval	7.8	7.5	3.9	3.6	12.4	2–17	26	1726–1930
Area-wide fire interval	18.8	17.4	11.7	7.0	32.0	6–39	12	1704–1930

Table 4.3B. Fire interval calculations for Kelley Mountain. Abbreviations: MFI = mean fire interval; WMI = Weibull median interval; SD = standard deviation; LEI = lower exceedance level; UEI = upper exceedance level.

Kelley Mountain	MFI	WMI	SD	LEI	UEI	Range	Number of intervals	Years covered
Point fire interval (n=92)	7.1	7.0	3.1	3.6	10.9	3–16	84	1725–1921
Stand-level composite fire interval								
Stand A (n=27)	5.5	5.3	2.3	2.8	8.2	3–12	25	1785–1921
Stand B (n=37)	6.3	5.5	5.2	1.8	11.6	1–29	28	1745–1921
Stand C (n=17)	5.7	5.3	3.3	2.2	9.5	2–13	32	1740–1921
Stand D (n=10)	6.7	6.2	4.3	2.4	12.0	2–16	27	1740–1921
Combined-stand composite fire interval	3.9	3.7	1.9	1.8	6.2	2–11	50	1725–1921
Filtered composite fire interval	5.8	5.5	3.1	2.5	9.4	2–15	34	1725–1921
Area-wide fire interval	7.8	7.0	3.6	3.8	12.1	2–16	25	1725–1921

Table 4.3C. Fire interval calculations for Reddish Knob. Abbreviations: MFI = mean fire interval; WMI = Weibull median interval; SD = standard deviation; LEI = lower exceedance level; UEI = upper exceedance level.

Reddish Knob	MFI	WMI	SD	LEI	UEI	Range	Number of intervals	Years covered
Point fire interval (n=76)	12.5	11.3	6.5	4.9	19.8	2–34	70	1676–1913
Stand-level composite fire interval								
Stand A (n=13)	9.5	9.1	5.0	4.3	15.0	4–20	25	1676–1913
Stand B (n=32)	6.5	5.8	4.7	2.0	11.7	2–19	30	1718–1913
Stand C (n=7)	9.6	8.6	6.3	3.2	16.8	2–19	14	1725–1913
Stand D (n=21)	7.1	6.2	5.5	2.0	13.1	2–23	28	1714–1913
Combined-stand composite fire interval	4.8	4.6	2.6	2.0	8.0	2–13	49	1676–1913
Filtered composite fire interval	8.2	7.4	5.6	2.7	14.4	2–26	29	1676–1913
Area-wide fire interval	8.8	8.0	5.7	3.0	15.0	2–20	27	1676–1913

I was able to determine the seasonality of 66% of the fire scars at Mill Mountain, 52.3% at Kelley Mountain, and 29.7% at Reddish Knob. Most of the scars were in the dormant position, but others occurred in the earlywood and latewood (Table 4.4).

Table 4.4 Seasonality of fire scars per study site. Seasonal designations include: (1) dormant, occurring between the latewood of one ring and the earlywood of the next (2) early, occurring within the first third of the earlywood, (3) middle, occurring within the second or last third of the earlywood, (4) late, occurring in the latewood band and (5) undetermined, seasonality of scar cannot be determined.

Site	% With Seasonality	% Seasonality Undetermined	Dormant Season	Early Season	Middle Season	Late Season
Mill Mountain	65.4	34.6	89.6	9.7	0	0.7
Kelley Mountain	52.3	47.7	86.1	10.0	3.9	0
Reddish Knob	29.7	70.3	56.5	20.2	16.9	6.4

Fire-climate Interactions

Analysis of fire events on Mill Mountain showed significant relationships at either $p < 0.05$ or $p < 0.025$ with negative PDSI values during the year of fire (t=0) in analysis of major fire events (MF), area-wide fire events (AW) and corresponding seasonality (Fig. 4.9). For Kelley Mountain, SEA indicated significant relationships ($p < 0.025$) three years prior to the fire event (t–3) for dormant season (ds) fires in all fire events (AF) and MF categories and one year prior to the fire event (t–1) for growing season (gs) fires in the AF and MF category (Fig. 4.10). Analysis for Reddish Knob showed significant relationships ($p < 0.025$) with negative PDSI during the year of the fire event (t=0) in the AF and AW categories (all seasons [as]) and significant relationships ($p < 0.05$) with negative PDSI during the year of the fire event ($t = 0$) in the MF/as category (Fig. 4.11). Region-wide analysis revealed statistically significant relationships with negative PDSI values for growing season burns (Fig. 4.12). Trends in fire activity and variations in moisture variability indicate that in general, fires were more numerous during periods in which PDSI values were negative (Fig. 4.13). Correlation analysis of PDSI with fire occurrence revealed statistically significant relationships at Mill Mountain, but not the other two sites or at the regional-level (Mill Mountain $r = -0.441$, $P = 0.031$, $df = 22$; Kelley Mountain $r = 0.028$, $P = 0.883$, $df = 28$; Reddish Knob $r = -0.054$, $P = 0.808$, $df = 24$; Region-level $r = -0.032$, $P = 0.891$, $df = 19$).

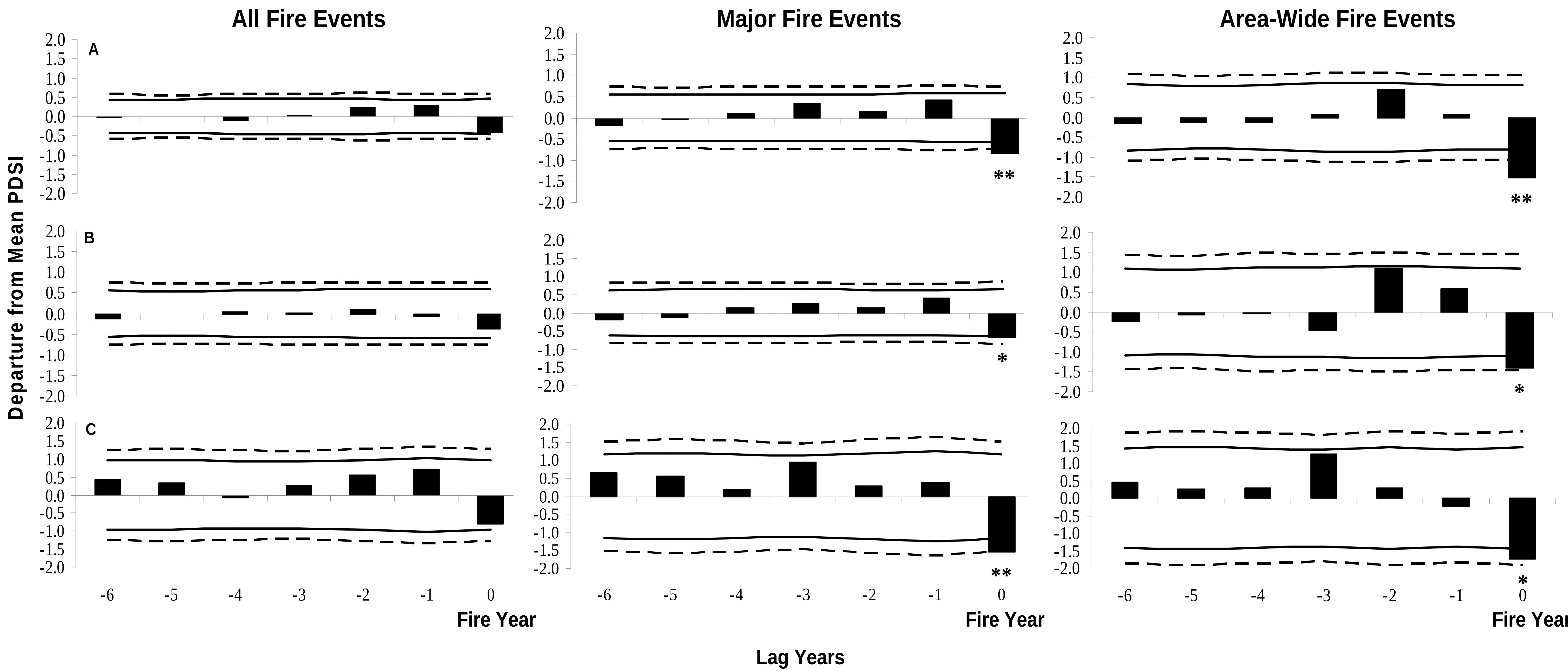

Figure 4.9 Results from superposed epoch analysis (SEA) for fire years represented by: All Fire Events (AF); Major Fire Events (MF); and Area-Wide Fire Events (AW) for Mill Mountain. Data is further divided according to seasonality of fire events: (A) All Seasons (as); (B) Dormant Season (ds); and (C) Growing Season (gs). Bars marked with ** indicate years for which actual moisture values vary significantly ($p < 0.025$) from simulated values. Bars marked with * indicate years for which actual moisture values vary significantly ($p < 0.05$) from simulated values.

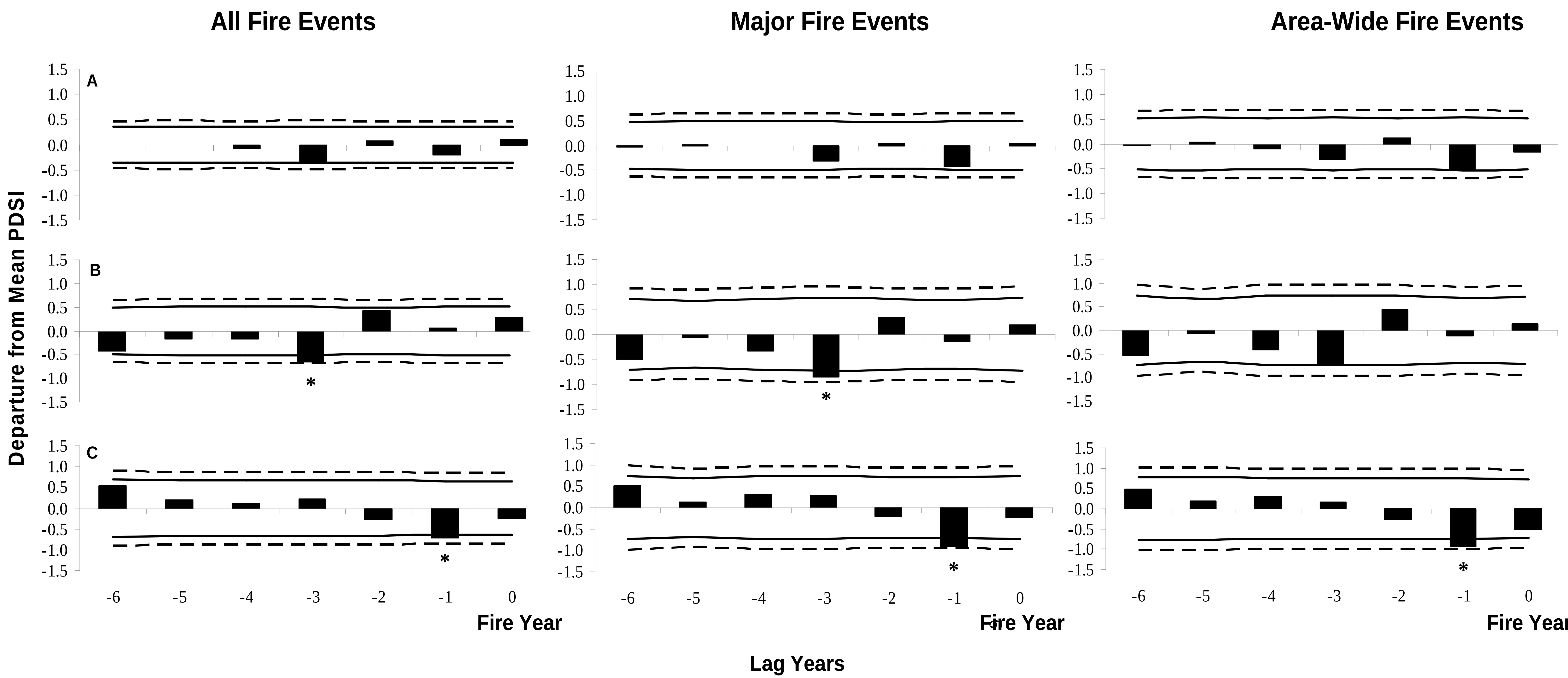

Figure 4.10 Results from superposed epoch analysis (SEA) for fire years represented by: All Fire Events (AF); Major Fire Events (MF); and Area-Wide Fire Events (AW) for Kelley Mountain. Data is further divided according to seasonality of fire events: (A) All Seasons (as); (B) Dormant Season (ds); and (C) Growing Season (gs). Bars marked with ** indicate years for which actual moisture values vary significantly ($p < 0.025$) from simulated values. Bars marked with * indicate years for which actual moisture values vary significantly ($p < 0.05$) from simulated values.

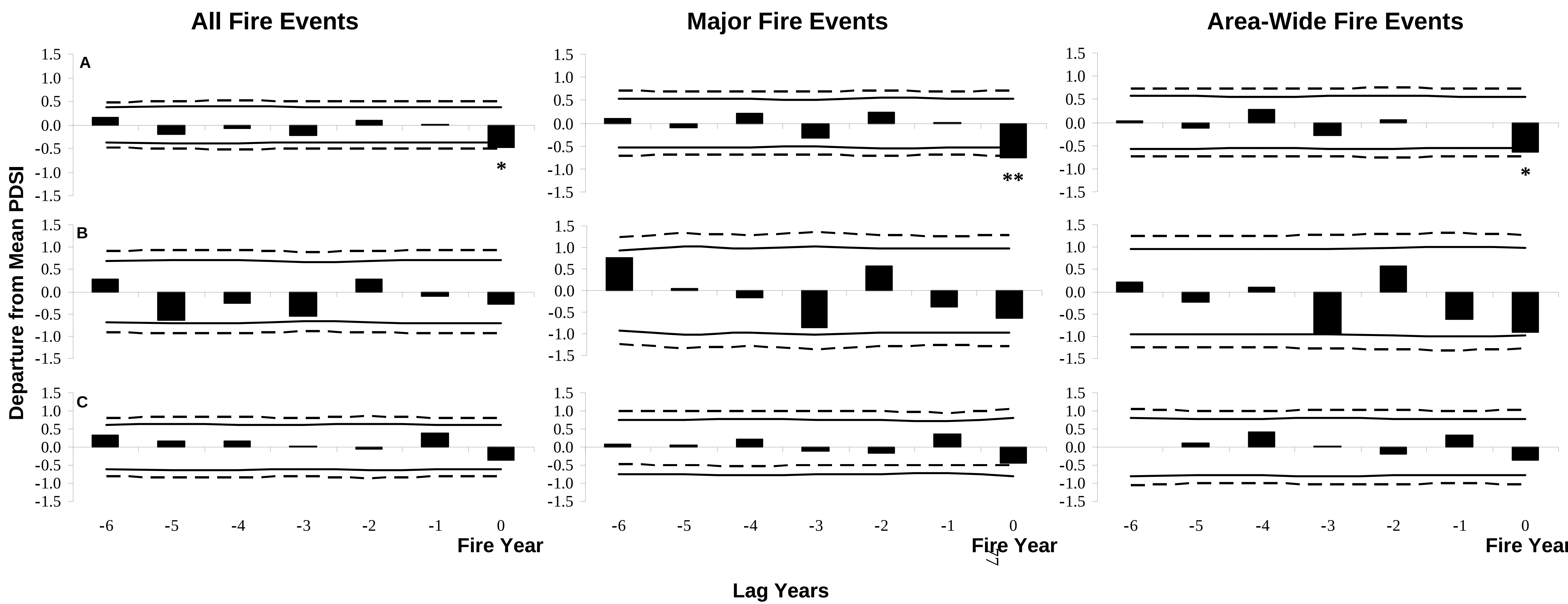

Figure 4.11 Results from superposed epoch analysis (SEA) for fire years represented by: All Fire Events (AF); Major Fire Events (MF); and Area-Wide Fire Events (AW) for Reddish Knob. Data is further divided according to seasonality of fire events: (A) All Seasons (as); (B) Dormant Season (ds); and (C) Growing Season (gs). Bars marked with ** indicate years for which actual moisture values vary significantly ($p < 0.025$) from simulated values. Bars marked with * indicate years for which actual moisture values vary significantly ($p < 0.05$) from simulated values.

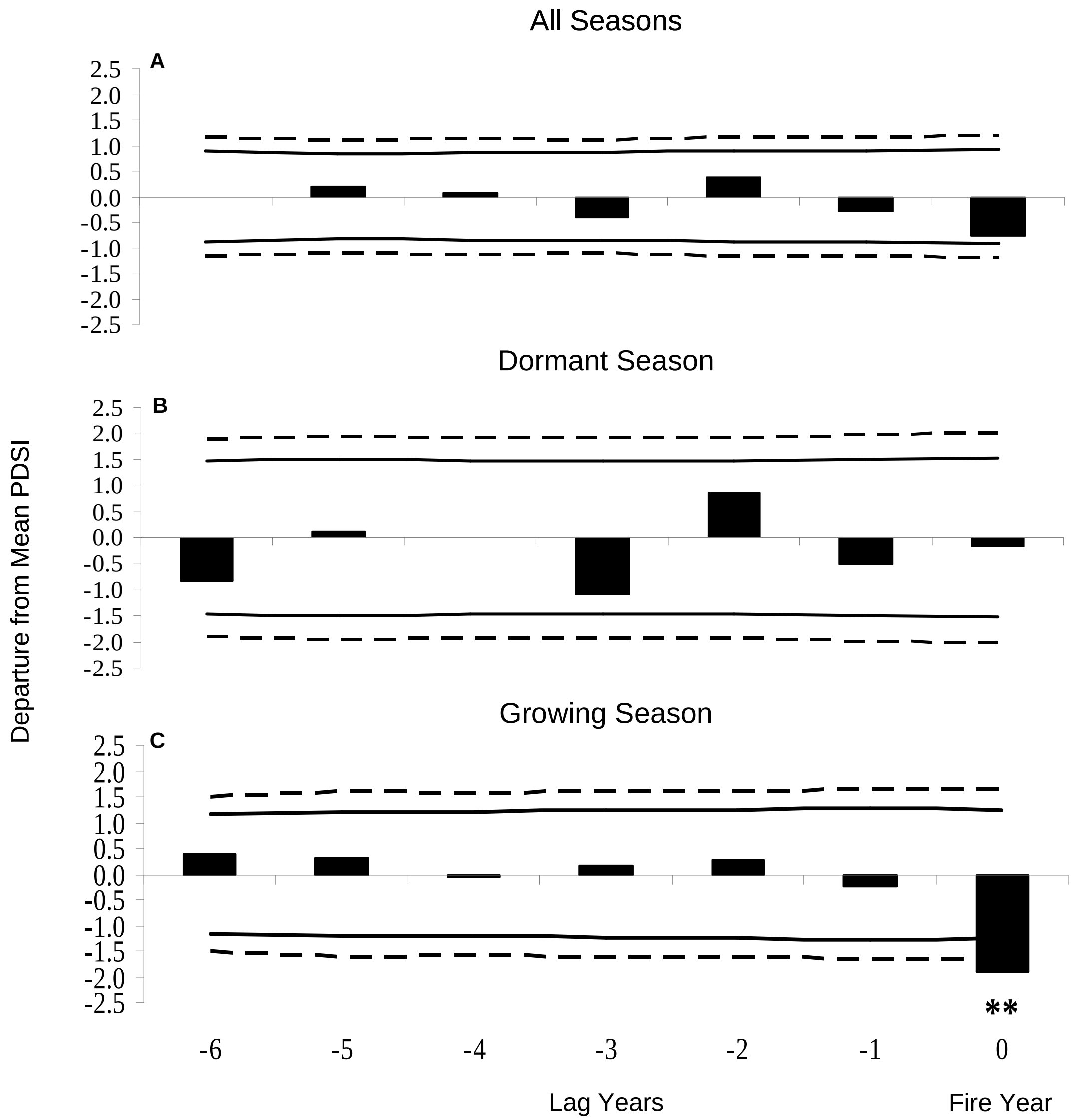

Figure 4.12 Previous and current year moisture conditions for fires represented by region-wide fire events. Data is further divided according to seasonality of fire events (A) all seasons; (B) dormant season (C) growing season burns. Bars marked with ** indicate years for which actual moisture values vary significantly ($p > 0.025$) from simulated values. Bars marked with * indicate years for which actual moisture values vary significantly ($p > 0.05$) from simulated values.

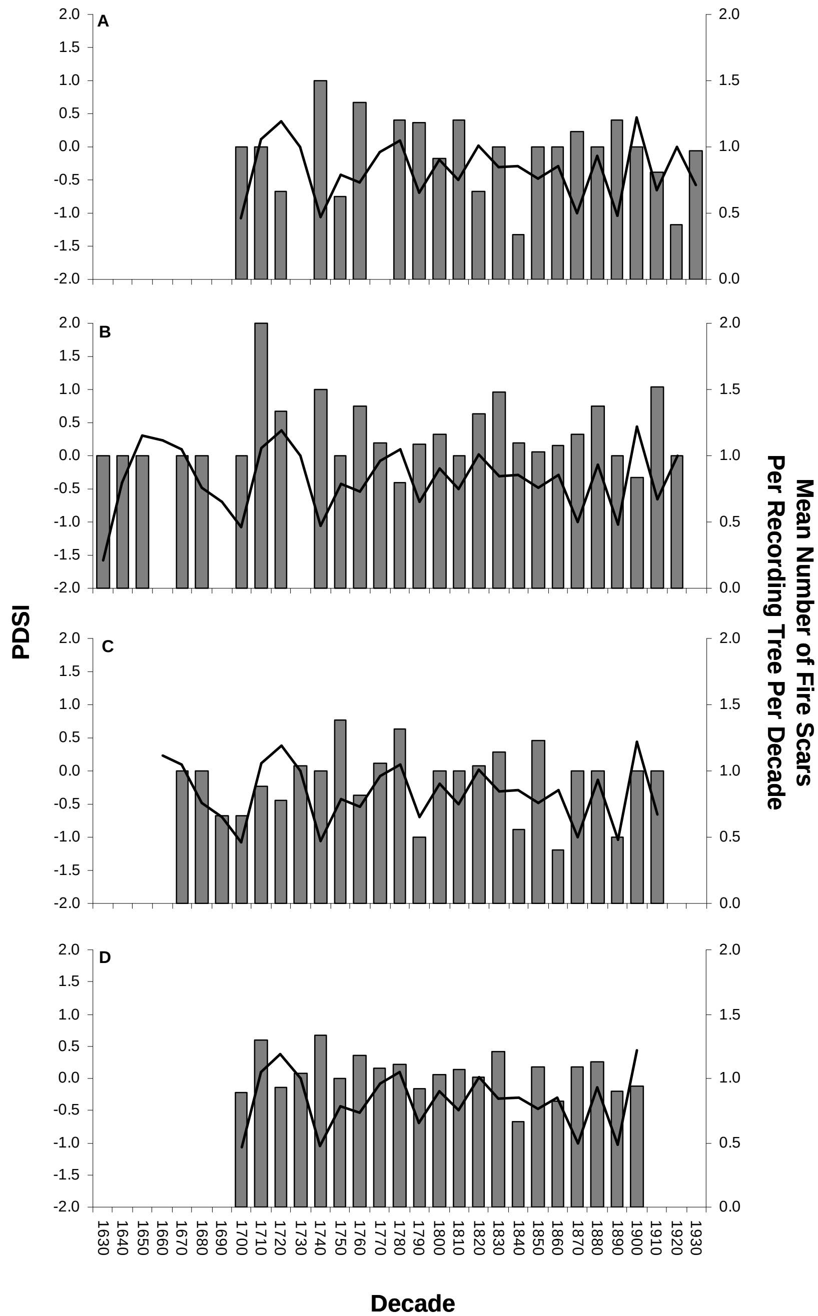

Figure 4.13 Comparison of fire activity and PDSI (A) Mill Mountain (B) Kelley Mountain (C) Reddish Knob and (D) Regional-level.

Vegetation Dynamics

Mill Mountain

Pine Stands

Pine establishment dates peaked on Mill Mountain during the 1900s–1920s for stands A and B, but in the 1870s–1880s for stand D (Fig. 4.14a). Cross-sections reveal earlier pine establishment, especially in the 1730s (Fig. 4.14b). Note that only fire-scarred cross-sections were collected from stand C; no plot was established. Table Mountain pine was the most abundant overstory species although pitch pine and Virginia pine was present as well (Table 4.5). Table Mountain pine was the only yellow pine species represented in the sapling and seedling inventory (Table 4.6).

Most hardwood trees were established during the 1920s–1940s (Fig. 4.14c, d) but some, chestnut oak and northern red oak were older. Chestnut oak was the dominant hardwood species in terms of basal area, but black gum, a non-oak hardwood species, was most abundant in terms of stem density (refer back to Table 4.5). Hardwood saplings and seedlings were more abundant in the understory than yellow pines. Mountain laurel established during the 1930s (Fig. 4.14e).

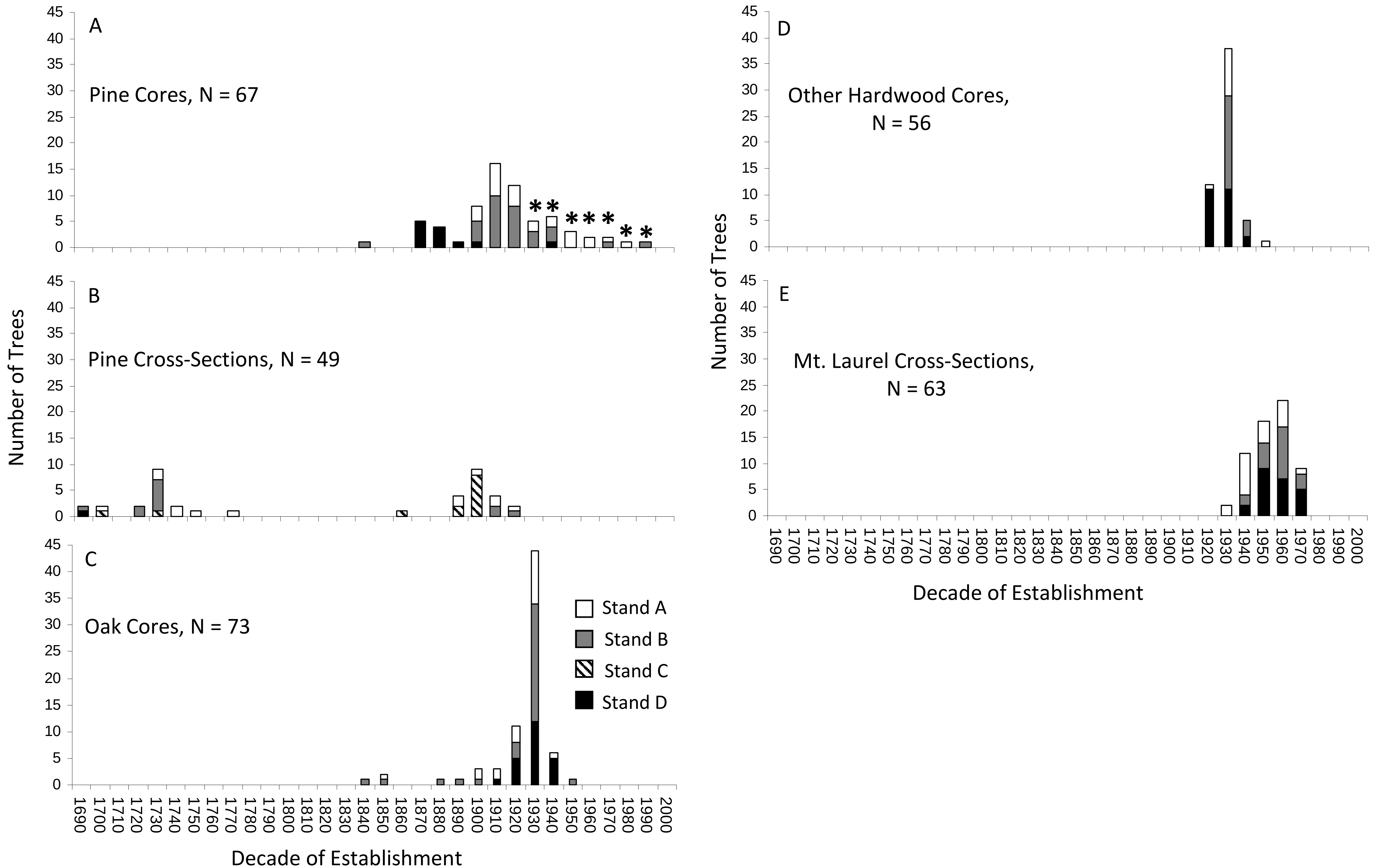

Figure 4.14 Mill Mountain tree establishment dates for trees cored in plots (A, C, D); (B) fire-scarred pines with intact pith and (E) mountain laurel shrubs. Asterisks indicate that one or more stems was a sapling aged by node-counting.

Table 4.5 Basal area and tree density for each study site. Oak stands on Mill Mountain were not sampled due to a prescribed burn in 2005 that affected the stands.

	Mill Mountain		Kelley Mountain				Reddish Knob			
	Pine Stands		Pine Stands		Oak Stands		Pine Stands		Oak Stands	
Species	Basal Area (m^2 ha^{-1})	Tree Density (stems ha^{-1})	Basal Area (m^2 ha^{-1})	Tree Density (stems ha^{-1})	Basal Area (m^2 ha^{-1})	Tree Density (stems ha^{-1})	Basal Area (m^2 h^{-1})	Tree Density (stems ha^{-1})	Basal Area (m^2 ha^{-1})	Tree Density (stems ha^{-1})
P. pungens	10.94	229.77	13.6	389.6	0.6	10.0	13.4	409.6	0.1	3.3
P. rigida	2.03	36.63	0.9	49.9	0.2	3.3	7.0	183.2	0.3	6.7
P. strobus			0.9	83.2	2.4	46.6				
P. virginiana	0.38	6.66		3.3	1.6	36.6				
Q. alba					2.3	16.7				
Q. coccinea	3.1	99.9		3.3			0.3	13.3	1.2	13.3
Q. montana	7.84	159.84	8.5	326.3	69.9	702.6	0.9	16.7	13.7	203.1
Q. rubra	0.46	23.31			23.3	3.9			4.4	46.6
Q. velutina	0.53	19.98			3.3	0.2			2.7	26.6
A. rubrum	0.02	3.33					0.7	93.2	1.6	139.9
A. saccharum									0.2	20.0
C. glabra	0.01	3.33			1.5	53.3			2.1	146.5
N. sylvatica	1.79	276.39	1.6	219.8	4.1	109.9	3.6	492.8	0.9	123.2
S. albidum				13.3						
Total	27.10	859.14	25.6	1095.6	86.8	1005.7	25.9	1208.8	27.2	729.3

Table 4.6 Sapling and seedling density for pine and oak stands at each site. No oak stands were sampled at Mill Mountain due to a prescribed burn conducted in 2005 that affected the site.

	Mill Mountain		Kelley Mountain				Reddish Knob			
	Pine Stands		Pine Stands		Oak Stands		Pine Stands		Oak Stands	
Species	Saplings Density (stems ha^{-1})	Seedlings Density (stems ha^{-1})	Saplings Density (stems ha^{-1})	Seedlings Density (stems ha^{-1})	Saplings Density (stems ha^{-1})	Seedlings Density (stems ha^{-1})	Saplings Density (stems ha^{-1})	Seedlings Density (stems ha^{-1})	Saplings Density (stems ha^{-1})	Seedlings Density (stems ha^{-1})
P. pungens	33.3	66.7	93.3	116.7	26.7	16.7				
P. rigida			3.3							
P. strobus		16.7	30.7	16.7	40.0					
P. virginiana			0.3	33.3	3.3	116.7				
Q. alba		83.3	0.3	16.7	110.0	350.0				
Q. coccinea	56.7	650.0	15.3		10.0	16.7	3.3			183.3
Q. montana	3.3	216.7	2.7	533.3	473.3	1800.0		133.3	266.7	1716.7
Q. rubra		416.7	0.7	16.7	273.3	800.0	30.0	950.0	53.3	1133.3
Q. velutina	13.3	166.7	1.0			133.3	20.0	116.7	100.0	666.7
A. pensylvanicum					56.7		3.3	2966.7	263.3	1450.0
A. rubrum	130.0	1250.0	65.0	733.3	483.3	3783.3	83.3	5533.3	243.3	6383.3
A. saccharum									3.3	283.3
C. anifolia			86.7	233.3						
C. dentata	30.0		6.7				3.3			
C. glabra							10.0		20.0	316.7
L. tulipifera										3.3
N. sylvatica	73.3	416.7	377.7	783.3	43.3	116.7	27.3	83.3	10.0	383.3
R. pseudoacacia			0.7		93.3	16,7	1.7		3.3	
S. albidum	3.3	983.3	2.3	816.7	10.0	2416.7		50.0		33.3
T. canadensis							3.3		70.0	

Kelley Mountain

Pine Stands

The peak establishment period for yellow pines on Kelley Mountain began the decade following the last major fire event in 1921, although establishment also occurred earlier (Fig. 4.15a, b). Note that only fire-scarred cross-sections were collected from stand D; no plot was established. Most white pine establishment occurred in the latter part of the 20th century (Fig. 4.15c). Most of the hardwood species established in the 1920s, but a few oaks were older (Figs. 4.15d, e). Table Mountain pine was the most abundant yellow pine in the overstory and most of the yellow pine saplings and seedlings were Table Mountain pine. The overstory hardwood component of the pine stands consisted primarily of chestnut oak and black gum (refer back to Table 4.5). Black gum and chestnut oak were the most abundant hardwood saplings. Sassafras (*Sassafras albidum*), black gum, and red maple seedlings were all abundant in the understory (refer back to Table 4.6). Mountain laurel began to establish in the 1920s in stand B, the 1930s in stands C and D, and the 1950s in stand A (Fig. 4.15f).

Oak Stands

Most hardwood trees established during the 1920s–1940s (Fig. 4.16a, b).There is a small pine component in these stands, most of which are yellow pine (Fig. 4.16c, d) was the most abundant oak species in the overstory, and black gum was the most abundant non-oak species (refer back to Table 4.5). Most hardwood saplings and seedlings were non-oak species primarily red maple, sassafras, and black gum.

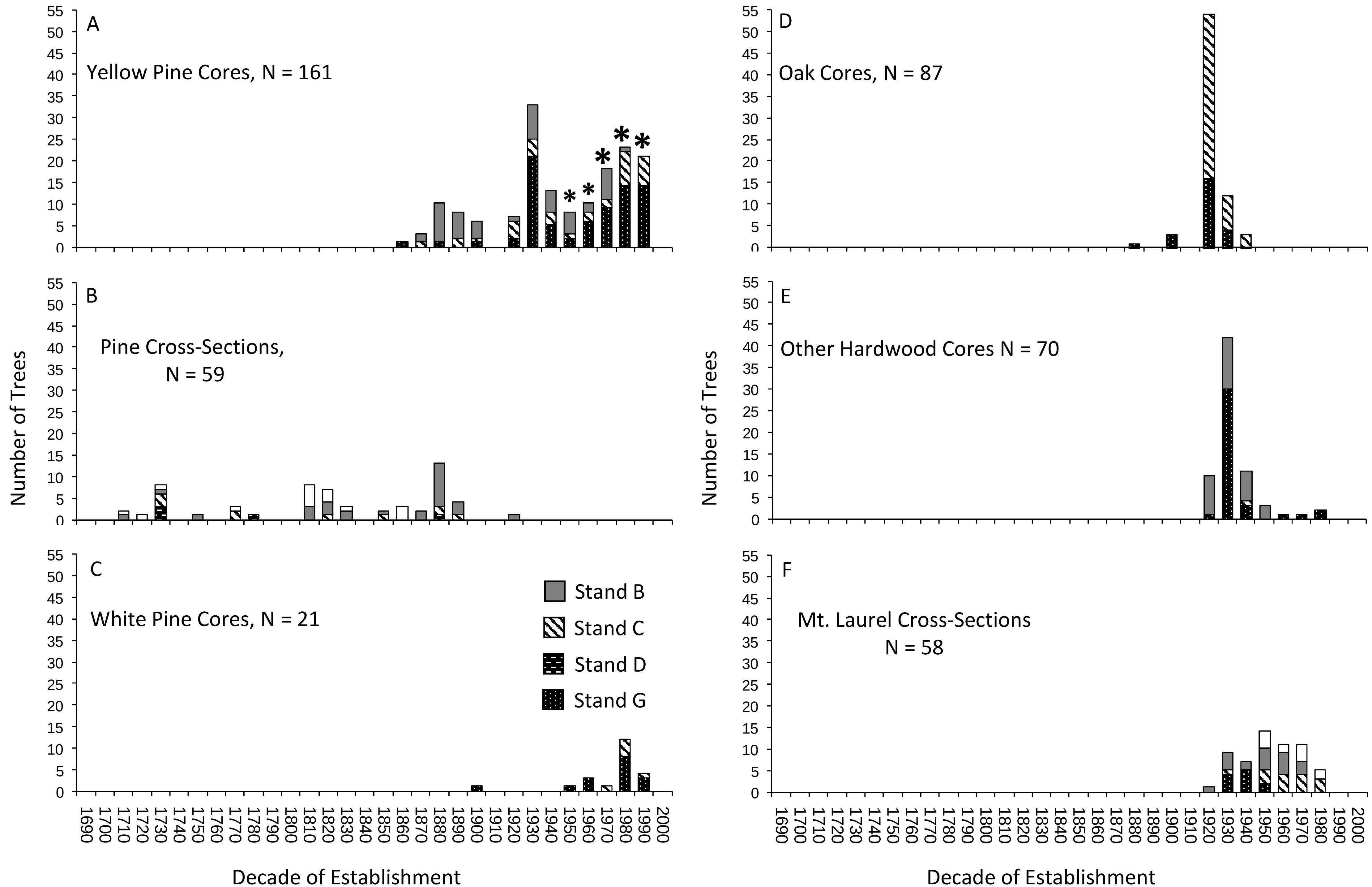

Figure 4.15 Kelley Mountain pine stand tree establishment dates for trees cored in plots (A, C, D, E); (B) fire-scarred pines with intact pith and (F) mountain laurel shrubs. Asterisks indicate that one or more stems was a sapling aged by node-counting

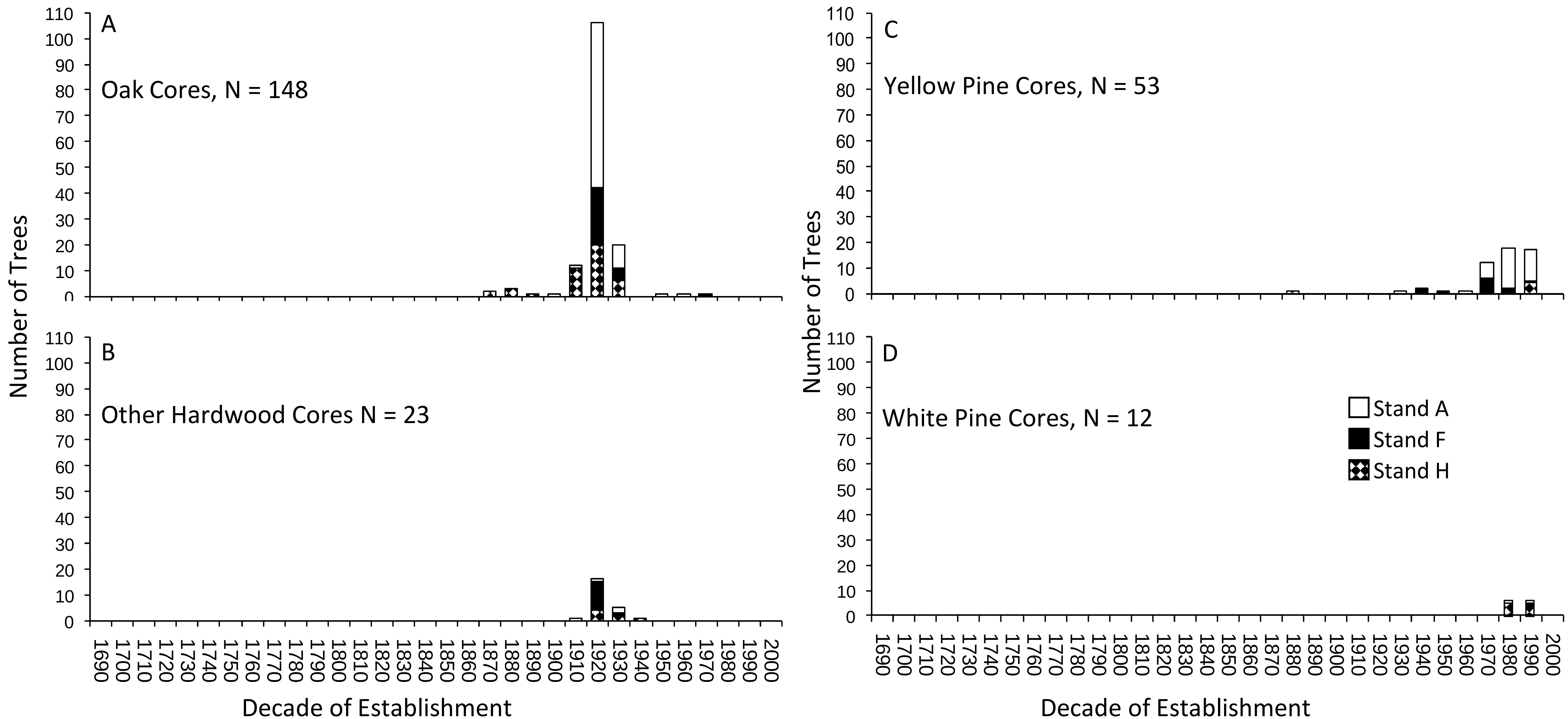

Figure 4.16 Kelley Mountain oak stand tree establishment dates for trees cored in plots (A, B, C, D).

Reddish Knob

Pine Stands

Yellow pine cores show establishment beginning in the 1860s with peak establishment occurring during the decade of the 1920s, particularly in stand A (Fig. 4.17a). Cross-sections record yellow pine establishment on Reddish Knob beginning in the mid 1600s with other pulses occurring during the periods 1690–1710; 1780–1790 and again from 1860–1880 (Fig. 4.17b). Note that only fire-scarred cross-sections were collected from stand D; no plot was established. The pine stands contained only two yellow pine species, Table Mountain pine and pitch pine (refer back to Table 4.5) and no yellow pine saplings or seedlings were recorded in any of the plots (refer back to Table 4.6). Hardwood establishment, both oak and non-oak species, began in the 1910s in stands A, B and C (Fig.4.17c, d). Black gum was the most abundant hardwood in the overstory, and red maple was the most abundant non-oak species in both sapling and seedling classes. Mountain laurel established in stands A and C during the 1910s and in stand B in the 1920s (Fig. 4.17e).

Oak Stands

Oak species established beginning in the late 1800s with a peak occurring in the decade of 1910 (Fig. 4.18a). Non-oak species began to establish in the 1900s and reached peak establishment in the 1910s (Fig.4.18b). Chestnut oak and northern red oak were the only oak species recorded and pignut hickory was the most abundant non-oak species (refer to Table 4.5). The sapling and seedling layers were dominated by red maple (refer back to Table 4.6).

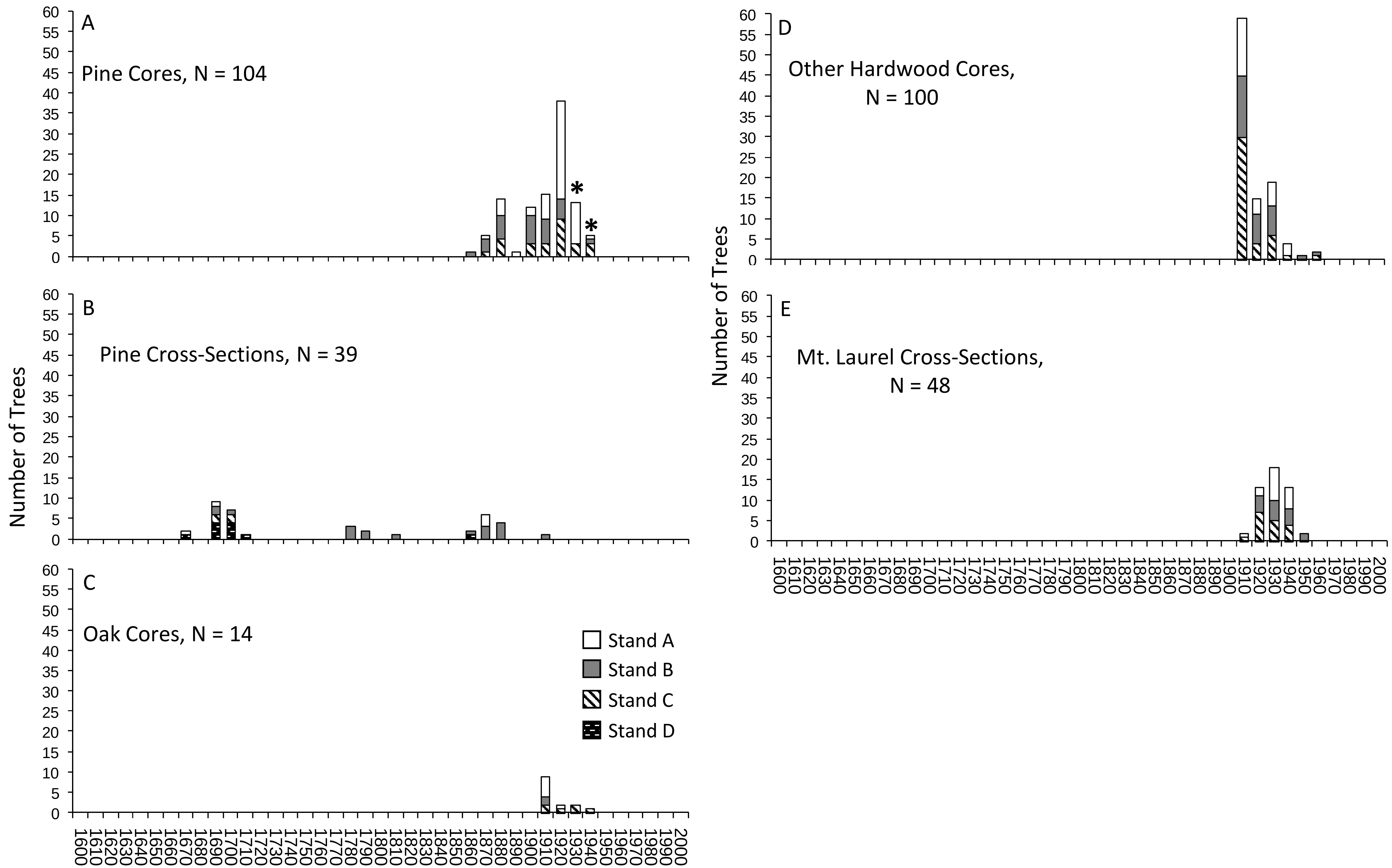

Figure 4.17 Reddish Knob pine stand tree establishment dates for trees cored in plots (A C, D); (B) fire-scarred pines with intact pith and (E) mountain laurel shrubs. Asterisks indicate that one or more stems was a sapling aged by node-counting.

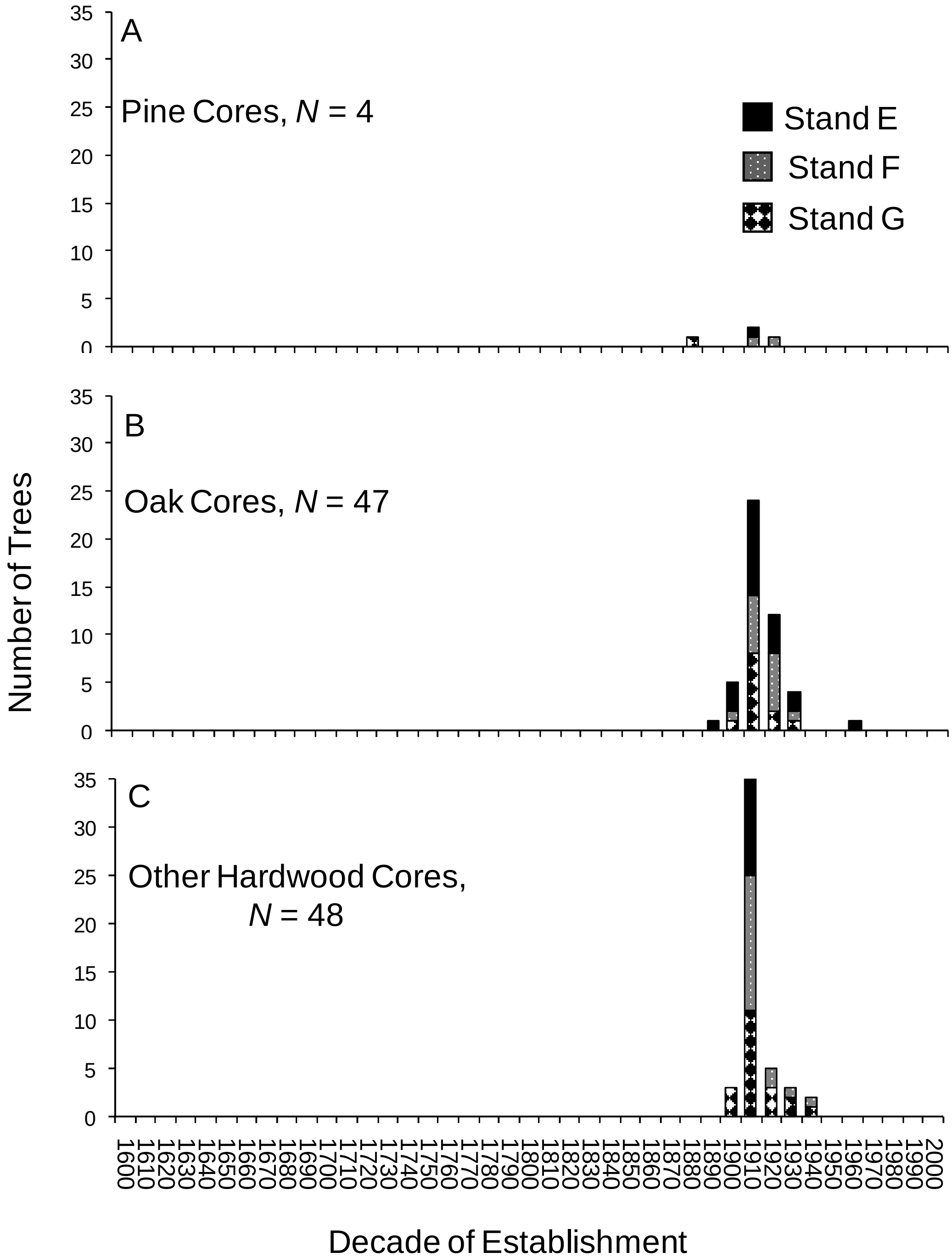

Figure 4.18 Reddish Knob oak stand tree establishment dates for trees cored in plots (A, B, C).

Radial Growth Releases

The peak decades for radial growth releases (in pine and hardwood cores combined) on Mill Mountain were the 1890s, 1960s, and 1980s (Fig. 4.19a). Oak stands were not sampled at Mill Mountain because of a prescribed burn in 2005 that affected the stands. On Kelley Mountain, radial growth releases peaked during the 1890s, 1930s, and 1960s (Fig. 4.19b). Reddish Knob radial growth releases peaked in the 1930s and 1960s Fig. 4.19c).

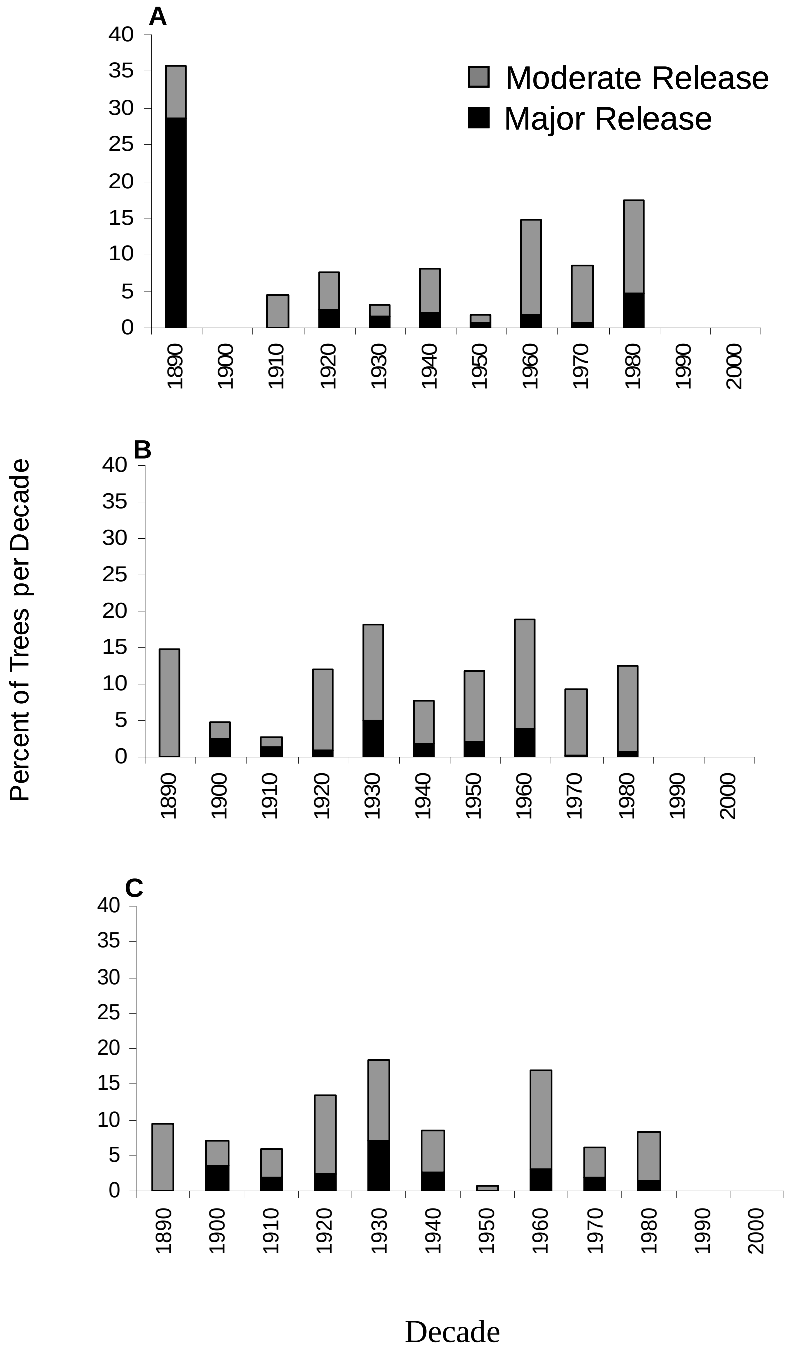

Figure 4.19 Percent of all trees (including pines and hardwoods) showing moderate and major release patterns each decade. (A) Mill Mountain 1880–1990 (period with ≥ 10 trees available to analyze; (B) Kelley Mountain 1880–1990; and (C) Reddish Knob 1880–1990.

CHAPTER V

DISCUSSION*

Fire History

Results of fire history analyses provide evidence of a long history of frequent fire at all study sites in the past. The composite fire intervals reported here are shorter than intervals reported in similar studies of Appalachian pine stands (Harmon, 1982 [12.7 yrs]; Sutherland *et al.*, 1995 [10 yrs]; Armbrister, 2002 [7.5 yrs]), however, this could be a function of sample size. Larger sample sizes would reduce the probability of missing smaller fires that may have only scarred a few trees in the stand (Kou & Baker, 2006). For example, some fire history studies in oak stands in the region had larger sample sizes and reported fire intervals closer to what I report here (Shumway *et al.*, 2001 [7.6 yrs]; McEwan, 2007 [2.1–12.2 yrs]; Hoss *et al.*, 2008 [2.5 yrs]). Even the more conservative fire interval estimates from this study reflect a frequent fire regime (i.e., < 25 year interval; Pyne *et al.*, 1996). Point fire intervals based on individual samples rather than the composite of all samples offer another useful, albeit conservative, estimate of fire frequency for any point on the landscape (van Horne & Fule´, 2006; Hoss *et al.*, 2008). Estimates of the point MFI indicate that fires burned somewhere on the landscape at intervals of approximately 7.1–12.5 years. The short interval for area-wide fires is consistent with the hypothesis (Harrod *et al.*, 2000) that historically, large-extent fires

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were common in xerophytic Appalachian forests and maintained open stands of highly flammable, grassy understories. Frequent burning would have limited fuel accumulation, thus supporting a regime dominated by low- to moderate-severity surface burns. In fact, the young age and small diameter of trees at initial scarring suggests that most fires were not intense (Aldrich *et al.*, 2010).

High fire frequency at Kelley Mountain was not unexpected because of the history of anthropogenic activity in the area after European settlement in the late 1700s. However, the high number of fires occurring prior to European settlement was surprising. For example, many samples had fire scars dating well before the first land grants were issued in the area, and one sample contained fire scars dating back to 1629. The frequency of fire at Mill Mountain and Reddish Knob, especially during the 1700s, was unexpected because of the remoteness of these sites. This pattern may be explained, in part, by lightning ignitions (Aldrich *et al.,* 2010). While anthropogenic ignitions dominate many fire regimes in humid, temperate forests (e.g., Guyette *et al.*, 2002; Lafon & Grissino-Mayer, 2007), recent work suggests that lightning ignitions are an important component of fire regimes in the Appalachian Mountains (Cohen *et al.*, 2007; Lafon & Grissino-Mayer, 2007). Both the Blue Ridge and the Ridge and Valley provinces are subject to thunderstorms generated by terrain-forced convection that occurs in association with high pressure conditions, but this is more pronounced in the Blue Ridge. The combination of high pressure that dries out fuel with increased lightning activity would elevate the importance of lightning in areas thought to be too humid for lightning ignitions (Lafon & Grissino-Mayer, 2007). This phenomenon may also explain high presettlement fire frequency reported in other Appalachian fire chronologies (Mann *et al.,* 1994; Shumway *et al.*, 2001).

Large fire size also may have contributed to high fire frequency. If large-extent fires were common, a relatively low density of ignitions by humans and/or lightning would be needed to maintain frequent burning (Harrod *et al.*, 2000). Large extent fires were not expected on this rugged landscape, but the frequent area-wide fires suggest that it was common for fires to spread across the hardwood-covered terrain and burn multiple pine stands (Aldrich *et al.,* 2010). The occurrence of large fires despite topographic barriers may be a function of high fire frequency. Harrod *et al.* (2000) hypothesized that frequent burning maintained open stands with contiguous fine fuels that would have diminished the effects of topography to the spread of fire, particularly in drought years. The spread of these large-extent fires into the more moist sites may have been important in maintaining oak abundance.

Temporal Changes in Fire Frequency

I expected to see an increase in fire frequency during the middle 1800s through the early 1900s concomitant with increasing industrial activity. However, little temporal variability is evident despite these dramatic changes on the surrounding landscape and variations in sample size between sites. A similar pattern was observed for an Appalachian oak forest in Maryland (Shumway *et al.*, 2001), but contrasts with the historic fire regime of the Ozark Plateau in the central U.S., where fire intervals for oak and pine forests declined in association with increases in human population density

(Guyette *et al.*, 2002; 2006). This suggests that on the most remote areas (Mill Mountain and Reddish Knob), the stability of the fire-return interval could relate to several factors other than anthropogenic ignitions: (1) lightning activity (Aldrich *et al.*, 2010); (2) obstruction if fire spread from human settlements because of topographic roughness (cf. Guyette *et al.*, 2002; Signell & Abrams, 2006) and (3) fuel moisture or fuel recovery rate, which could limit fire spread and mitigate temporal variability even if ignition rate increased (Guyette *et al.*, 2002) and (4) large fire size. The stability of the fire regime at Kelley Mountain is likely a combination of fuel characteristics and ample ignition sources (both natural and anthropogenic).

The only pronounced temporal change in fire frequency was the cessation of burning that coincided with USFS acquisition and the advent of effective fire control (Aldrich *et al.*, 2010). This change, evident at all three locations, was clearly associated with alterations in human activity and represented a complete break with the previous record of frequent fire. For example, the time since last fire on Reddish Knob is 92 years, over 19 times the length of the composite fire interval for 1676–1913. Kelley Mountain and Mill Mountain show similar trends (Kelley Mountain, 83 years; Mill Mountain, 71 years).

Fire-climate Interactions

The results of the regional-scale fire-climate analyses were what I had expected to observe at this scale of study. In general, relationships between fire activity and climate often only emerge at larger spatial scales and over longer time periods (Swetnam

& Brown, 2010) due to influences of governing mechanisms (e.g. climate, fuel, topography, fire regime properties) that vary according to scale (Falk *et al.*, 2007). At small spatial and temporal scales, fire behavior is a function of fuel (type, moisture, and continuity), local weather conditions (air temperature, humidity, and wind speed) and microtopography (Barton, 1999; Falk *et al.*, 2007). At broader scales, fire occurrence and behavior is influenced by other factors such as stand-level vegetation, macrotopography, seasonal weather and synoptic climate (Falk *et al.*, 2007). As such, the results of my site-level fire-climate analysis were unexpected. Fire activity was found to be strongly correlated with negative PDSI values during the year of drought (t=0) at both Mill Mountain and Reddish Knob, but the relationship was more pronounced at Mill Mountain, particularly for dormant season major fire and area-wide fire events. The strength of this correlation at Mill Mountain may have been augmented by several years of above-average precipitation prior to the year of fire that might have limited fire activity and accentuated the production of fuel, thus allowing for more intense, wide-spread fires in particularly dry years. Likewise, the relative isolation of the site from anthropogenic activity may have been a factor as well.

Correlation analysis did not reveal a statistically significant fire-climate relationship at Reddish Knob, even though SEA revealed significant relationships between fire occurrence and year of drought (t=0) in the all season category at all scales of study (all fire events, major fire events, and area-wide fire events). The strength of the fire-climate correlation could be influenced by anthropogenic ignitions in the region that may have somewhat subdued the strength of the climate signal. Nonetheless, SEA does provide evidence of a pattern between fire activity and drought at this site as well.

The equivocal results reported by SEA for Kelley Mountain was the pattern that I expected to see. Superposed Epoch Analysis showed fire activity was strongly correlated with negative PDSI values three years prior to the fire year (*t*-3) during the dormant season of the AF and MF analysis, and one year prior to fire (*t*-1) during the growing season in all three analyses. It appears that Kelley Mountain was greatly impacted by human activity, more than Mill Mountain or Reddish Knob, and fires were frequent, regardless of above- or below-average precipitation. Similar patterns were observed in mixed-oak forests in southern Ohio by Sutherland (1997) and McCarthy *et al.* (2001), and a mixed-oak forest in eastern West Virginia (Schuler & McClain, 2003). As in these studies, the ambiguous results obtained for Kelley Mountain may be a function of high fire frequency due to human activity in the area, which could obscure the climate signal. For example, in a fire-prone Madrean forest in the lower Rhyolite Canyon of southeast Arizona, Barton *et al.* (2001) found a similar lack of correlation between below-average precipitation and fire activity. The study site was located in close proximity to areas supporting high populations of indigenous peoples during the 19th century. Human-ignited fires associated with this habitation may have attributed to the high fire frequency that would obscure the connection between natural climate patterns and fire activity. Similarly, in a study conducted in the Boston Mountains of Arkansas, Guyette *et al.* (2006) found that the relationship between fire and climate was stronger during periods of low population density and that fire frequency was influenced more by anthropogenic activity than climate during periods of high population density.

Natural processes may have acted to influence the fire regime of Kelley Mountain as well, thus making the climate signal more difficult to detect. One of these is the natural flammability of the area. In an investigation of contemporary patterns of fire occurrence in the central Appalachian Mountains, Lafon & Grissino-Mayer (2007) found that climatically, the Blue Ridge (the location of the Kelley Mountain site) is more fire-prone than the Ridge and Valley (the location of Mill Mountain and Reddish Knob sites). While the amount of precipitation each area receives annually is relatively equivalent, the seasonality of the precipitation is distributed differently. For example, in non-drought years, precipitation in the Ridge and Valley is more evenly distributed throughout the year, thus limiting prolonged periods of dry weather that would favor fire activity (Lafon & Grissino-Mayer, 2007). Conversely, the precipitation regime of the Blue Ridge is characterized by less frequent precipitation events that deliver heavy rainfall. This would lead to longer dry periods that may increase the flammability and probability of ignition in the area. In fact, Lafon & Grissino-Mayer, (2007) found that the peak of the natural fires in the Blue Ridge coincides with the period of lower precipitation levels.

Because of the ‘noise’ introduced by site-specific processes operating at local spatial scales, it is useful to examine fire-climate relationships at regional scales and over longer time periods (Brose *et al.*, 2001; Swetnam & Brown, 2010). For example the effects of climate on fire activity can be inferred by broad-scale synchrony (or asynchrony) of fire events among widely dispersed regions. Many studies in the western US have been successful in elucidating these relationships by using a network of sites distributed across mountain ranges or regions (e.g., Swetnam & Betancourt, 1998; Veblen *et al.*, 1999; Brown & Sheppard, 2001; Sibold & Veblen, 2006; Brown, 2006; Kitzberger *et al.*, 1997; Swetnam & Brown, 2010), but little work has been done in the southeastern US. I plan to combine my region-wide fire chronology with chronologies developed by DeWeese (2007) and Hoss *et al.* (2008) in an effort to expand the spatial and temporal scale of analysis for the central Appalachian region.

Vegetation Dynamics

Woody species that exist in fire-prone environments can be differentiated by their ability to resist fire (i.e., surviving relatively unharmed) or to endure fire (i.e., sprouting after top-kill) (Rowe, 1983; Lloret & Vila, 2003). Of particular relevance to this study is the hypothesis that the fire regime may control the balance of pine and oak wherever they coexist in fire-prone environments (Barton, 1999). Under this hypothesis, pines are predicted to be favored under a regime of moderate fire frequency and intensity, while oaks should benefit from a regime of lower fire frequency and intensity.

Investigation of age structure, basal area, and stem density in the pine stands suggests that pines were more successful under frequent burning than oaks. The polymodal establishment pattern of pines suggests they may have been able to take advantage of regeneration opportunities provided by occasional severe fires that may have opened the canopy and reduced understory vegetation. Table Mountain pines produce serotinous cones at an early age that would allow for continuous seedling germination under a regime of frequent fire. The seedlings grow quickly and once established are able to resist mortality from frequent, mild surface burns because of their thick, protective bark.

While both Table Mountain pine and pitch pine have specific traits that aid in their persistence on fire-prone landscapes, pitch pine in this study was less favored. Both species produce cones at an early age, but production of cones in pitch pine is less regular and seed production more variable than in Table Mountain pine. Also pitch pine seeds do not remain viable in the seed bank (1 year; Gucker, 2007) as long as Table Mountain pine seed (5–9 years; Della-Bianca, 1990; Reeves, 2007). Even though pitch pine can sprout post-fire, the sprouts grow more slowly than seedlings, especially in trees that have been exposed to repeat burning (Gucker, 2007). In areas with shallow soil, which is characteristic of these study sites, high-severity fires may kill or damage pitch pine roots by heating the mineral soil (Gucker, 2007). Thus frequent burning may have gradually filtered out pitch pine and promoted Table Mountain pine.

The pulses of pine establishment in the 1880s and 1890s (Kelley Mountain and Reddish Knob) and the 1900s (Mill Mountain) may have been the result of severe fires, but other disturbances such as insect outbreaks, storms and droughts are common in the Appalachian region as well (White, 1987; Lorimer, 2001; Waldron *et al.*, 2007; Aldrich *et al.* 2010). It is likely the pines established as a result of a combination of disturbances. For example, extensive insect outbreaks (apparently southern pine beetle) were reported in Bath County *c.* 1895–1900 (Mill Mountain; Morton, 1917); Augusta County *c.* 1880

(Kelley Mountain; GWNF land record files) and Rockingham County *c* 1890 (Reddish Knob; GWNF land record files). The development of the current overstory likely reflects the influence of multiple interacting disturbance agents, but fire appears to be the most important (Lafon & Kutac, 2003; Aldrich *et al.*, 2010). In the absence of fire, canopy gaps created by occasional insect outbreaks or storms will not be enough to perpetuate pine recruitment because of the dense hardwood understory (Aldrich *et al.*, 2010). In fact, at Mill Mountain, disturbances in the 1930s, 1960s and 1980s (implied by growth releases) during the era of fire exclusion were not followed by pine establishment. Consequently, as the overstory pines senesce and die, there may not be sufficient young pines in the understory to replace them (Aldrich *et al.*, 2010). This is especially important at Reddish Knob where no Table Mountain pine seedlings or saplings were found in the plots during sampling.

In contrast to the establishment patterns observed for the pines under frequent fire, age structure suggests that chestnut oak established within a relatively narrow window of time and maintained a low presence in the pine stands until fire exclusion allowed their abundance to increase. This is consistent with the hypothesis of Barton (1999) and Abrams (1992) that oaks fare better under a regime of low-intensity fire at a lower frequency. Chestnut oak is relatively fire-resistant at maturity compared to other oaks in the region (e.g. northern red oak, black oak and white oak [Carey, 1992]), and requires a fire-free interval of about 14 years to generate sufficient bark thickness to survive low-intensity surface fires (Carey, 1992). Thus, the fire intervals reported in this study would be sufficient to suppress the establishment of chestnut oak regardless of its ability to sprout prolifically after top-kill. In the decades immediately following the last fire, the abundance of chestnut oak increased. That the oaks were able to respond so quickly after the elimination of fire suggest that seedlings and sprouts were already present in the understory, and the reduced frequency of fire provided an environment conducive to their maturation (Carey, 1992; Barton, 1999). Barton (1999) predicted that a decline in fire frequency should favor oaks because lack of fire increases canopy cover and litter depth, preventing successful seedling recruitment in pines. At the same time, prolific basal and lateral sprouting would lead to increased abundance of oak (Barton, 1999). However, complete removal of fire has resulted in the regeneration failure of oaks as well as pines and this pattern is clearly evident in the age structure graphs. In mature stands with dense overstory/understory vegetation, oak seedlings are often numerous, but too small to compete with taller saplings of other species (Lorimer *et al.*, 1994; van Lear, 2004). Canopy gaps created by occasional disturbances do not usually benefit oak regeneration in these stands because overstory removal facilitates the release and spread of faster growing, shade tolerant species. Consequently, oak species are being replaced on good quality sites (Abrams, 1992; Lorimer *et al.*, 1994; van Lear, 2004; Signell *et al.*, 2005).

Chestnut oak dominates the east-facing slopes of Kelley Mountain and Reddish Knob and apparently was more successful than pines in these stands, even under a regime of frequent fire. The fire regime of the intervening chestnut oak stands was similar in frequency to those of the pine stands (as indicated by frequent, area-wide fires that burned through oak stands were recorded in all pine stands), but may have been less intense because of the potentially moister microsite conditions on the east-facing slopes. As in the pine-dominated stands, frequent fire would encourage sprouting and maintain conditions favorable for seedling establishment, but lower fire intensity may have allowed more oak seedlings and sprouts to survive over time.

The paucity of oak establishment in both the pine and oak stands prior to the mid- to late-1800s must be interpreted with care because much of the oak on Kelley Mountain and Reddish Knob was removed by logging. Likewise, many of the chestnut oak sampled were undatable because of sapwood decay and are not included in the age structure analysis. However, because oak forests have dominated much of the eastern forest from the early Holocene (Braun, 1950; Abrams, 1992; Whitney, 1994) it is likely that oak existed on these sites, at least the east-facing slopes, during presettlement times.

It is generally accepted that the abrupt shift in fire regimes in the twentieth century has led to altered vegetation composition and structure throughout the US (Nowacki & Abrams, 2008), and many studies have documented these changes (e.g. Heinselman, 1973; Abrams & Nowacki, 1992; Wolf, 2004; DeWeese, 2007; Hoss *et al.*, 2008; Aldrich *et al.*, 2010). In this study, the large pulse of tree and shrub establishment in the 1900s is unique in the age structure and not observed in the past when the disturbance regime was dominated by frequent fire. Fire-sensitive species such as black gum and red maple were not evident in the age structure graphs until the 1900s, but were probably present on more mesic sites (riparian areas, coves) and later invaded the stands (Abrams & McCay, 1996; Abrams, 2003; Signell & Abrams, 2006); or they may have been present in the understory, but were relegated to small-scale rocky features that served as refugia from fire (Signell & Abrams, 2006). The "interface" (Barton, 1999) between the period of high fire frequency and the beginning of fire exclusion provided optimal conditions for the establishment of not only pine and oak, but other woody species as well. Similar patterns were noted in several Table Mountain pine stands (DeWeese, 2007) and a chestnut oak-dominated stand (Hoss *et al.*, 2008) in the central Appalachian Mountains of Virginia.

Nowacki & Abrams (2008) argued that fire suppression initially leads to increases in stand-level richness as a new suite of tree species recruits into tree-size classes, but over time this pattern likely will reverse itself as older pine and oak are replaced by shade-tolerant species through gap-phase replacement. This trend is clearly evident on all of the study sites and is consistent with the predictions of the Dynamic Equilibrium Model (Huston, 1979), which states that species diversity depends on the balance between rates of competitive displacement and frequency of disturbance. In low-productivity communities (e.g. xerophytic Appalachian pine stands) that experience high frequencies of disturbance, diversity should be low because not all species are able to recover from high rates of population reduction. But a decline in disturbance frequency should promote higher species diversity on these sites, consistent with the successional trends suggested by my results.

The large pulse of tree recruitment in the 1900s coupled with the removal of fire has led to forests that are denser than in presettlement time. Calculations of basal area and stem density are indicative of stands with a high density of trees of small diameter. Many of these are hardwood stems characteristic of forests that do not experience periodic fire. While I have no presettlement reference conditions with which to compare the density of these stands, this pattern is consistent with findings of Nowacki & Abrams (2008) that state modern forests are denser than presettlement forests and much of the increase is in trees of small diameter classes.

The increase of mountain laurel in the 1920s and 1930s added to the overall density of the pine stands. Mountain laurel likely was present in the understory prior to the 1900s, but frequent burning probably prevented it from becoming abundant (Clinton *et al.*, 1993). Mountain laurel is common on a variety of landscapes in the eastern US and it is believed to have increased in abundance in the recent past as a result of canopy disturbance (loss of the American chestnut, gypsy moth (*Lymantria dispar*) defoliation, and logging) and fire suppression. Mountain laurel is moderately shade-tolerant but grows best in open areas. It is also a prolific sprouter that is able to quickly take advantage of canopy gaps created by disturbance. These characteristics make mountain laurel an important competitor against slower growing pine and oak species in areas with infrequent fire. Some studies of *Kalmia* species in boreal forests suggest that allelopathic properties of the shrubs may contribute to conifer regeneration failure (Mallik, 2003), however, studies in the eastern US (Swift *et al.*, 1993) suggest that pine and oak regeneration failure in stands with a dense mountain laurel component is due to increased shading in the understory that prohibits established seedlings from recruiting into the overstory. In stands containing abundant populations of mountain laurel, species that are able to survive in shaded conditions are more likely to recruit into the overstory (Clinton *et al.*, 2003). A study documenting the regeneration history of Table Mountain pine-pitch pine stands in Georgia (Brose *et al.*, 2002) suggested that regeneration of all tree species, regardless of their shade tolerance, ceased after large numbers of mountain laurel established. Brose *et al.* (2002) predicted these stands would eventually convert from Table Mountain pine-pitch pine forests to mountain laurel thickets if the shrub is not controlled. Studies of prescribed burns in pine and oak stands have shown that mountain laurel responds well to fire and may regain its dominance in the understory within a few years of a single burn treatment (Ducey *et al.*, 1996; Elliott *et al.*, 1999). Multiple-burn treatments have shown equivocal results in controlling the abundance of mountain laurel (cf. Clinton *et al.*, 1993; Moser *et al.*, 1996; Arthur *et al.*, 1998), but prescribed burns in combination with mechanical treatments may be more successful (Swift *et al.*, 1993; Clinton & Vose, 2000).

Shifts from conifer forests to ericaceous heathlands have been documented in other ecosystems. For example in some nutrient-poor conifer forests with dense ericaceous shrub understories, the combination of (1) suppression of natural high-severity fires (2) rapid regeneration of shrubs following canopy opening by logging or low-severity fires and (3) habitat degradation due to allelopathic properties of the shrubs has led to the replacement of dominant species from conifers to ericaceous shrubs (Mallik, 1995; 2003).

A possible consequence of increasing stand densities is a phenomenon called ‘mesophication’, whereby dense shading not only inhibits the success of shade-intolerant species, but may lead to microenvironmental changes in the understory that can reduce the flammability of the system (Nowacki & Abrams, 2008). Dense shading promotes moister, cooler microclimates which favor mesophytic species. The mesophytic species, in turn, produce less flammable fuels that decay quickly in the moist understory, further reducing the flammability of the system. This cycle is reinforced by positive feedback cycle in which conditions continually improve for mesophytic species and deteriorate for xerophytic species (Nowacki & Abrams, 2008).

This trend is likely to continue as long as fire is excluded from these systems, and may not be easily reversed with the reintroduction of fire (Nowacki & Abrams, 2008). Vegetation changes due to mesophication occur more quickly and are more difficult to reverse on more productive sites because plants that are adapted to low resource conditions (i.e., xerophytic pine and oak) do not compete as well on productive sites as plants adapted to high resource conditions (i.e., mesophytic hardwoods and shrubs; Smith & Huston, 1989; Nowacki & Abrams, 2008). Conversely, on less productive xeric sites, these changes generally occur more slowly because plants adapted to high resource levels cannot compete as well when resources are limited (Smith & Huston, 1989). However, the shift from xerophytic to mesophytic species may be accelerated on resource-poor landscapes if the understory contains a high number of mesophytic species and a limited pool of fire-adapted replacement species (Smith & Huston, 1989; Nowacki & Abrams, 2008).

CHAPTER VI

CONCLUSIONS AND IMPLICATIONS[*]

Fire scar evidence is consistent with the view that burning occurred frequently in forest ecosystems of eastern North America, even before European settlement. Fire was a common and widespread occurrence at all three study sites, even at Mill Mountain, which was more isolated from human influence. Fire frequency remained relatively constant despite changes in land use until the beginning of fire exclusion in the early 20th century.

Results of SEA provide evidence that periodic droughts may be important drivers of fire activity. Drought the year of fire was important on both Mill Mountain and Reddish Knob, regardless of the proximity of the sites to anthropogenic activity. Other dendroecological studies of eastern forests (Schuler & McClain, 2003; McEwan *et al.*, 2007) report more equivocal results of fire-climate relationships and suggest that high frequency of fire in areas of high anthropogenic activity may obscure the climate signal. Investigations of contemporary fire regimes of the central Appalachian Mountains (Lafon *et al.*, 2005) show a strong relationship between climate and fire, particularly in terms in drought. More research is needed to disentangle the effects of climate from human activity on the fire regime.

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Vegetation development clearly was influenced by fire. The results presented here are consistent with a polycyclic fire regime of frequent surface fires that maintained open understory conditions in the montane pine stands, and occasional more severe fires that contributed to pine recruitment episodes. The intervening oak stands experienced the same fire frequency as the pine stands, but the fires may have been less intense, favoring oak over pine. There is little evidence that industrial disturbances altered the past fire regime or vegetation at Mill Mountain; however, these disturbances may have been more important on Kelley Mountain and Reddish Knob especially for the present composition of the forests.

It is clear from this study and others in the eastern US that the xerophytic composition of these forests is shifting from fire-tolerant pines and oaks to more mesic, fire-intolerant hardwoods and shrubs. Restoration efforts that include prescribed burning are being implemented to curtail these shifts, but much still needs to be learned for these efforts to be successful. This study provides direct evidence of a long history of frequent fire in xerophytic Appalachian forests and changes in vegetation structure and composition in the context of multiple land-use episodes. The presettlement origin of the yellow pine stands and widespread oak regeneration failure coupled with the history of frequent fire and near complete removal of fire in recent decades make these forests an important conservation priority.

Even though it is increasingly clear that fire is an important missing component in contemporary forests, reintroducing fire into these systems will not necessarily produce an immediate shift to vegetation conditions of the past. A potential obstacle is the dense hardwood understory that developed as a consequence of fire exclusion (Aldrich *et al.*, 2010) that may change the way these forests respond to fire (Turrill, 1998). In the past, fire may have maintained open understories, but today prescribed burns can actually increase mid- and understory densities (Turrill, 1998). For example, several studies (Elliott *et al.*, 1999; Waldrop & Brose, 1999; Welch *et al.*, 2000) of post-fire regeneration after single prescribed burns in Appalachian pine stands show that pine seedling density increased, but the seedling density of unwanted hardwoods also increased, and at greater rates due to their superior sprouting ability. Studies in some oak stands (McGee *et al.*, 1995; Kuddes-Fischer & Arthur, 2002; Gilbert *et al.*, 2003) show that the application of single prescribed fires were of little benefit to oak regeneration, in part because fire has been absent from these stands so long that fire-sensitive species have grown large enough to survive moderate surface fires (Signell & Abrams, 2006). Likewise, individual canopy-opening disturbances can accelerate shifts in vegetation composition if sufficient numbers of shade-tolerant species are present in the understory prior to the disturbance (Lorimer *et al.*, 1994; Signell *et al.*, 2005). Similarly, in certain stands where ericaceous shrubs such as mountain laurel dominate the understory, individual disturbances may facilitate conversion from forests to heathland (Mallik, 1995).

Repeated burning over several years at intervals similar to those reported here, combined with mechanical or chemical thinning may be necessary to control the hardwood/shrub component and reduce litter accumulations (Lorimer *et al.*, 1994; Brose & van Lear, 1998; Elliott *et al.*, 1999; Welch *et al.*, 2000; van Lear, 2004; Brose *et al.*, 2005). Signell *et al.* (2005) report increased success when prescribed burns are preceded by mechanical thinning. Thinning of understory vegetation provides the opportunity for oaks to establish, and then prescribed fires are applied to stimulate sprouting. It is urgent that such actions take place in the near future while mature seed-producing trees and flammable xerophytic vegetation remain (Nowacki & Abrams, 2008).

Understanding disturbance history is important for explaining contemporary vegetation patterns and guiding restoration efforts (Signell & Abrams, 2006; Aldrich *et al.* 2010). The importance of fire as a disturbance agent in humid temperate forests is increasingly becoming apparent and often incorporated into management prescriptions, especially in ecosystems where land use changes have diminished the historic role of fire (White, 1987; Brose *et al.*, 2001; Nowacki & Abrams, 2008; Aldrich *et al.*, 2010). Dendroecological studies, such as this one, that incorporate fire history, climate-fire relationships and vegetation dynamics provide a foundation on which to build effective management prescriptions. This study provides not only site-specific evidence, but also elucidates broader regional trends in burning and vegetation responses to fire. The fire chronologies developed for this study are among the longest and most thorough from eastern North America and are consistent with the view that burning was a frequent and important disturbance agent in eastern North America from presettlement times until the implementation of fire protection (Aldrich *et al.*, 2010).

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APPENDIX A

STANDARD TREE-RING CHRONOLOGY TABLES

A1. Standard tree-ring chronology for Mill Mountain. These values are the tree-ring indices for each year in the chronology. The indices are displayed without the decimal points, but the actual value can be obtained by dividing the numbers by 100. The mean value for all indices is 1.0. Each line represents one decade of indices and the decades are shown in the lefthand column. The numbers across the top of the table are the last numbers of the decade year for each decade. This is called the"Tucson format" and is the internationally accepted format of the World Data Center for Paleoclimatology.

Year	0	1	2	3	4	5	6	7	8	9
1687								2125	2113	2065
1690	1985	1237	1157	1244	1625	1053	538	574	284	644
1700	548	404	658	650	907	1070	1565	1243	684	1058
1710	1060	950	698	711	937	959	1297	1066	1019	726
1720	661	780	529	568	671	708	523	603	617	724
1730	1150	1168	914	1044	1053	941	984	814	1019	1345
1740	657	545	761	913	1029	1049	793	1020	859	1296
1750	1633	1332	872	1043	1196	694	1376	1062	732	1008
1760	1389	1132	849	901	1085	1002	1135	1073	945	1227
1770	994	1314	908	1119	992	1154	1088	727	1344	1022
1780	612	806	676	953	878	884	956	904	964	878
1790	851	842	852	1011	1044	840	960	767	827	770
1800	1092	1233	1380	1096	911	920	767	1295	1439	1470
1810	1294	1356	1063	1092	1300	1408	1077	1484	1363	1027
1820	1130	1069	861	834	811	977	831	969	987	1076
1830	816	846	1164	876	985	963	879	683	666	792
1840	1038	1050	1189	947	874	633	800	831	877	898
1850	924	1280	1085	982	1252	1191	722	880	987	1195
1860	1371	1497	1181	982	799	917	779	1019	845	827
1870	761	728	605	779	719	754	974	821	1119	769
1880	997	760	1299	1010	1151	725	1190	875	1171	1315
1890	1095	854	915	851	821	593	764	1008	1192	1103
1900	943	1118	1200	1416	981	924	1099	1179	1463	910
1910	958	938	1349	1538	1057	1093	1485	1014	1168	944
1920	1010	887	997	871	1235	931	1006	1381	1437	1667
1930	670	896	718	1102	826	1256	838	1131	1140	1062
1940	992	664	819	879	456	967	1030	1162	1540	1429
1950	1275	1216	791	883	814	991	931	829	922	723
1960	680	934	820	936	1111	988	695	1318	1156	989
1970	735	752	763	940	1330	1021	1208	1122	844	581

A1. Standard tree-ring chronology for Mill Mountain (continued).

Year	0	1	2	3	4	5	6	7	8	9
1980	726	874	823	698	872	993	751	775	927	1213
1990	1213	1289	818	926	1193	1251	1201	1282	1002	775
2000	1409	1043	975	1004	1819					

A2 Standard tree-ring chronology for Kelley Mountain.

Year	0	1	2	3	4	5	6	7	8	9
1602			677	536	832	885	754	690	1011	826
1610	1071	1251	1202	1298	1484	841	1291	1797	1211	1069
1620	808	1499	1419	1402	1132	793	904	599	547	580
1630	947	856	812	1536	1420	658	554	507	1497	1637
1640	1372	1595	807	1259	1321	1153	1302	997	713	1039
1650	732	1165	761	895	1008	901	959	999	1008	1290
1660	1921	1144	1625	1070	1046	1161	1046	1422	1685	1077
1670	930	623	361	418	401	419	805	1090	964	1190
1680	731	663	748	921	1008	1022	1091	999	1259	712
1690	898	379	306	836	1242	1372	1643	1509	1191	829
1700	1413	1126	1085	1068	992	917	880	680	464	1077
1710	1311	778	1177	1324	612	986	1139	911	1038	1015
1720	986	1001	916	675	919	814	879	905	1388	1020
1730	923	685	769	790	1024	821	931	842	1083	1115
1740	544	757	831	896	1007	1209	1188	1429	1161	1480
1750	1457	1253	1009	1332	1341	648	1223	1018	871	1100
1760	1580	1294	856	887	1067	715	1070	1106	1091	832
1770	1238	1020	620	921	619	538	687	659	970	990
1780	820	1063	802	1248	881	616	917	942	1159	1101
1790	1032	824	838	1106	1268	1103	1383	770	885	914
1800	1188	1073	1330	967	850	927	791	1121	1175	1421
1810	1190	1121	1060	723	1312	1294	1035	1371	1349	863
1820	660	810	891	888	761	954	1197	1164	782	1336
1830	1164	1196	1130	1185	1241	1276	1117	807	953	726
1840	1036	804	1062	734	950	219	566	716	800	780
1850	936	723	816	925	1393	515	431	627	913	790
1860	816	1070	1224	778	622	1069	730	1025	774	699
1870	887	1186	1029	1299	1282	1183	1585	1483	1676	1109
1880	1188	822	1445	970	1140	620	593	321	619	1326
1890	1101	1067	1025	1481	1293	958	604	887	1115	910
1900	977	1091	1204	1326	1051	1129	1043	851	1202	1052
1910	914	688	1108	1352	839	818	947	662	965	1009
1920	1128	796	1046	695	1050	655	853	1011	1292	1706
1930	883	1226	823	1203	1038	1104	1001	1067	1154	1231
1940	956	736	801	773	664	790	832	1259	1408	1446
1950	1605	1426	968	882	1149	945	1004	917	800	725
1960	884	1001	898	913	758	780	475	1042	974	935
1970	802	726	703	832	1335	1226	1006	792	918	766
1980	812	1023	987	874	1207	1055	572	636	812	943
1990	1263	1320	763	1054	1484	1225	1225	1549	1367	917
2000	1263	1026	878	903	1170	951				

A3 Standard tree-ring chronology for Reddish Knob.

Year	0	1	2	3	4	5	6	7	8	9
1671		1258	798	860	1106	1115	1252	1980	1490	1191
1680	1281	1332	1310	1118	1156	901	1117	1420	351	202
1690	335	738	643	986	1407	1027	806	1078	1042	1050
1700	1084	1068	1210	985	1010	1078	1152	1116	1137	1189
1710	1183	1008	794	780	637	635	705	600	800	759
1720	623	806	766	917	686	749	611	804	953	1172
1730	1353	1243	1119	1155	1119	1039	1314	646	912	1296
1740	903	876	1216	974	1295	1419	1044	1228	786	923
1750	1039	1032	767	828	879	598	1348	961	909	1199
1760	1333	1085	771	1161	1304	1024	1378	1247	1171	1352
1770	1199	1021	748	1191	979	1311	1441	1162	1802	1180
1780	576	854	691	672	561	706	930	815	894	796
1790	764	703	867	1062	1113	1077	1026	911	877	949
1800	1109	870	538	473	712	923	865	1220	1300	1201
1810	1137	1412	1114	1057	1532	1501	1204	1158	1198	886
1820	829	586	720	581	802	851	991	1147	1165	1206
1830	905	1065	1301	1004	1035	1078	1021	950	784	675
1840	1019	922	1269	809	999	586	678	785	859	794
1850	783	1044	1055	979	1013	815	757	944	1062	710
1860	947	1134	1068	923	716	888	1002	953	722	772
1870	795	776	894	1138	972	885	985	907	1110	659
1880	728	789	1145	1009	1134	807	1242	1061	1086	1349
1890	1237	1326	1160	974	962	849	888	983	910	829
1900	734	840	879	1080	916	894	1137	1473	1381	1065
1910	1129	774	1464	1263	855	902	1291	941	1217	927
1920	1024	898	901	986	1239	1120	1168	1353	1351	1639
1930	827	1072	681	972	1145	1217	760	1064	1377	1152
1940	911	850	871	882	513	970	1189	1028	1391	1422
1950	1139	1346	903	859	814	1125	1029	1032	1040	792
1960	628	649	813	991	1190	708	592	1035	981	754
1970	950	790	803	900	1158	961	1329	737	1175	815
1980	911	1080	958	703	887	1148	803	740	842	1312
1990	926	1596	782	661	1050	1128	1092	1360	1440	825
2000	1897	1210	906	900	1471					

APPENDIX B

STATISTICAL DESCRIPTIONS TABLES

B1 Statistical descriptions of each ring-width series in the Mill Mountain chronology.

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
1	MMA020A	1909	2003	95	0.743	0.279
2	MMA026B	1918	2003	86	0.700	0.286
3	MMA047	1905	2003	99	0.678	0.273
4	MMA050	1909	2003	95	0.708	0.284
5	MMA062	1907	2003	97	0.699	0.296
6	MMB051A	1914	2004	91	0.768	0.267
7	MMB064	1921	2004	84	0.682	0.283
8	MMB068	1919	2004	86	0.770	0.284
9	MMD017A	1877	2004	128	0.657	0.340
10	MMD023B	1899	2004	106	0.759	0.252
11	MMD043	1884	2004	121	0.615	0.280
12	MMD079	1881	2004	124	0.602	0.305
13	MMD080B	1894	2004	111	0.601	0.316
14	MMD099A	1851	1980	130	0.682	0.294
15	MMD100A	1855	2004	150	0.554	0.314
16	RKX001B	1840	2003	164	0.592	0.313
17	RKX010B	1862	2003	142	0.511	0.265
18	RKX014	1869	1995	127	0.679	0.273
19	RKX016	1869	2003	135	0.525	0.310
20	RKX017	1883	2003	121	0.637	0.273
21	XMMA100	1779	1917	139	0.466	0.266
22	XMMA101	1800	1919	120	0.547	0.333
23	XMMA102B	1760	1891	132	0.553	0.266
24	XMMA105	1777	1859	83	0.379	0.336
25	XMMA108	1760	1850	91	0.472	0.278
26	XMMA115A	1713	1845	133	0.560	0.278
27	XMMA116A	1790	1990	201	0.590	0.299
28	XMMA117	1751	1837	87	0.429	0.253
29	XMMA118A	1750	1879	130	0.477	0.266
30	XMMA119B	1748	1828	81	0.596	0.318
31	XMMA121	1732	1803	72	0.530	0.343
32	XMMB101	1732	1779	48	0.700	0.314

B1 Statistical descriptions of each ring-width series in the Mill Mountain chronology (continued).

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
33	XMMB105A	1732	1808	77	0.611	0.287
34	XMMB106	1734	1867	134	0.537	0.299
35	XMMB113B	1734	1860	127	0.541	0.248
36	XMMB117	1687	1894	208	0.412	0.267
37	XMMB119A	1762	1897	136	0.491	0.221
38	XMMB120	1733	1846	114	0.544	0.286
39	XMMB123A	1744	1897	154	0.494	0.241
40	XMMB124	1760	1817	58	0.644	0.335
41	XMMD107	1738	1794	57	0.488	0.287
Total:		**1713–2003**		**4674**	**0.582**	**0.286**

B2 Statistical descriptions of each ring-width series in the Kelley Mountain chronology.

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
1	KMA137A	1890	2005	116	0.740	0.321
2	KMA143A	1879	1915	37	0.693	0.361
3	KMA151A	1858	1940	83	0.652	0.304
4	KMA154B	1864	1970	107	0.600	0.397
5	kma159b	1938	2002	65	0.701	0.328
6	KMA161B	1867	1957	91	0.741	0.378
7	KMB001B	1894	2005	112	0.612	0.297
8	KMB009B	1886	2005	120	0.638	0.232
9	KMB020A	1925	2005	81	0.801	0.259
10	KMB028A	1896	2005	110	0.689	0.232
11	KMB078B	1888	2005	118	0.645	0.301
12	KMB102B	1890	2005	116	0.660	0.310
13	KMB109B	1883	2002	120	0.616	0.261
14	KMB111A	1865	2005	141	0.506	0.227
15	KMC006B	1931	2005	75	0.649	0.270
16	KMC019B	1904	2005	102	0.644	0.344
17	XKMA	1810	1920	111	0.695	0.357
18	XKMA101A	1825	1908	84	0.553	0.396
19	XKMA104B	1813	1940	128	0.717	0.333
20	XKMA106	1864	1997	134	0.617	0.359
21	XKMA108A	1714	1784	71	0.431	0.338
22	XKMA108B	1793	1908	116	0.614	0.407
23	XKMA111	1815	1897	83	0.629	0.338
24	XKMA112A	1776	1920	145	0.509	0.363
25	XKMA114B	1835	1924	90	0.660	0.387
26	XKMA116B	1812	1910	99	0.648	0.439
27	XKMA118A	1777	1852	76	0.612	0.334
28	XKMA119A	1824	1931	108	0.639	0.319
29	XKMA121	1814	1945	132	0.639	0.334
30	XKMA127	1753	1863	111	0.616	0.302
31	XKMA129A	1829	1950	122	0.522	0.420
32	XKMA501A	1730	1842	113	0.504	0.379
33	XKMA502A	1741	1800	60	0.562	0.258
34	XKMB130B	1869	2005	137	0.502	0.273
35	XKMB136	1810	1883	74	0.433	0.393

B2 Statistical descriptions of each ring-width series in the Kelley Mountain chronology (continued).

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
36	XKMB137	1833	2005	173	0.611	0.277
37	XKMB139	1840	1970	131	0.573	0.329
38	XKMB143	1891	1980	90	0.660	0.294
39	XKMC109A	1602	1793	192	0.526	0.269
40	XKMC114	1735	1800	66	0.509	0.308
41	XKMC115	1754	1823	70	0.684	0.319
42	XKMC118	1734	1814	81	0.611	0.376
43	XKMD103	1930	2005	76	0.706	0.268
44	XKMD104B	1735	1837	103	0.521	0.267
45	XKMD105B	1737	1766	30	0.533	0.299
46	XKMD107	1734	1819	86	0.548	0.316
47	XKMD108A	1739	1821	83	0.603	0.290
48	XKMD113A	1676	1709	34	0.613	0.205
Total:		**1602–2005**		**4803**	**0.611**	**0.320**

B3 Statistical descriptions of each ring-width series in the Reddish Knob chronology.

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
1	RKA028A	1881	2003	123	0.579	0.326
2	RKA053	1885	2003	119	0.729	0.298
3	RKA102	1880	1964	85	0.650	0.222
4	RKA201	1885	2003	119	0.639	0.342
5	RKA205	1883	2004	122	0.702	0.279
6	RKA234B	1884	2004	121	0.583	0.307
7	RKB003A	1884	2003	120	0.729	0.306
8	RKB009A	1883	2003	121	0.559	0.330
9	RKB023B	1867	1960	94	0.711	0.373
10	RKB029B	1873	1958	86	0.529	0.274
11	RKB030B	1886	2003	118	0.693	0.318
12	RKB031B	1886	1960	75	0.692	0.287
13	RKB042	1898	2003	106	0.718	0.316
14	RKB210A	1892	2004	113	0.639	0.314
15	RKB260B	1879	2003	125	0.657	0.226
16	RKC003A	1889	2004	116	0.782	0.361
17	RKC009B	1886	2004	119	0.614	0.308
18	RKC035B	1892	1970	79	0.700	0.389
19	RKC118B	1890	1980	91	0.602	0.315
20	XRKA100	1700	1789	90	0.527	0.293
21	XRKA108	1869	2003	135	0.560	0.313
22	XRKA113	1672	1855	184	0.510	0.292
23	XRKA115A	1725	1781	57	0.572	0.296
24	XRKA136	1754	1779	26	0.667	0.313
25	XRKB101	1671	1801	131	0.559	0.323
26	XRKB105	1746	1783	38	0.634	0.272
27	XRKB107	1884	1950	67	0.400	0.321
28	XRKB108	1887	1940	54	0.519	0.308
29	XRKB111	1726	1782	57	0.691	0.322
30	XRKB114A	1722	1803	82	0.435	0.385
31	XRKB115	1794	1854	61	0.630	0.311
32	XRKB123	1735	1893	159	0.529	0.339
33	XRKB124	1800	1930	131	0.557	0.262
34	XRKB125A	1701	1800	100	0.600	0.359
35	XRKB125B	1800	1970	171	0.537	0.296

B3 Statistical descriptions of each ring-width series in the Reddish Knob chronology (continued).

	Series	Interval		No. of Years	Correlation with Master	Mean Sensitivity
36	XRKB126	1806	1990	185	0.635	0.271
37	XRKB127A	1793	1840	48	0.575	0.335
38	XRKB127B	1850	2003	154	0.498	0.311
39	XRKB128	1786	1950	165	0.629	0.301
40	XRKB129	1789	1900	112	0.583	0.324
41	XRKB131	1699	1970	272	0.537	0.317
42	XRKB132	1810	1930	121	0.614	0.271
43	XRKB135	1694	1790	97	0.488	0.384
44	XRKB136	1698	1800	103	0.618	0.263
45	XRKB140	1789	1840	52	0.469	0.287
46	XRKC101	1754	1857	104	0.586	0.273
47	XRKC102	1726	1800	75	0.636	0.292
48	XRKC103	1698	1827	130	0.590	0.266
49	XRKC104B	1755	1864	110	0.633	0.302
50	XRKC105	1700	1787	88	0.651	0.314
51	XRKC110	1700	1760	61	0.640	0.349
52	XRKC111A	1699	1775	77	0.616	0.315
53	XRKC111B	1757	1801	45	0.522	0.298
54	XRKD102	1708	1860	153	0.565	0.273
55	XRKD108	1729	1800	72	0.615	0.357
56	XRKD110	1764	1800	37	0.657	0.317
57	XRKD111	1679	1744	66	0.666	0.303
58	XRKD112	1710	1779	70	0.498	0.258
59	XRKD113	1701	1848	148	0.577	0.334
60	XRKD116A	1695	1815	121	0.497	0.336
61	XRKD116B	1830	1885	56	0.509	0.298
62	XRKD122	1708	1768	61	0.519	0.304
63	XRKD128	1679	1719	41	0.466	0.433
64	XRKD138	1757	1833	77	0.578	0.248
65	XRKD139	1739	1863	125	0.488	0.294
66	XRK001	1718	1789	72	0.653	0.320
67	XRK002	1710	1870	161	0.608	0.308
Total:		**1671–2003**		**6854**	**0.594**	**0.308**

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